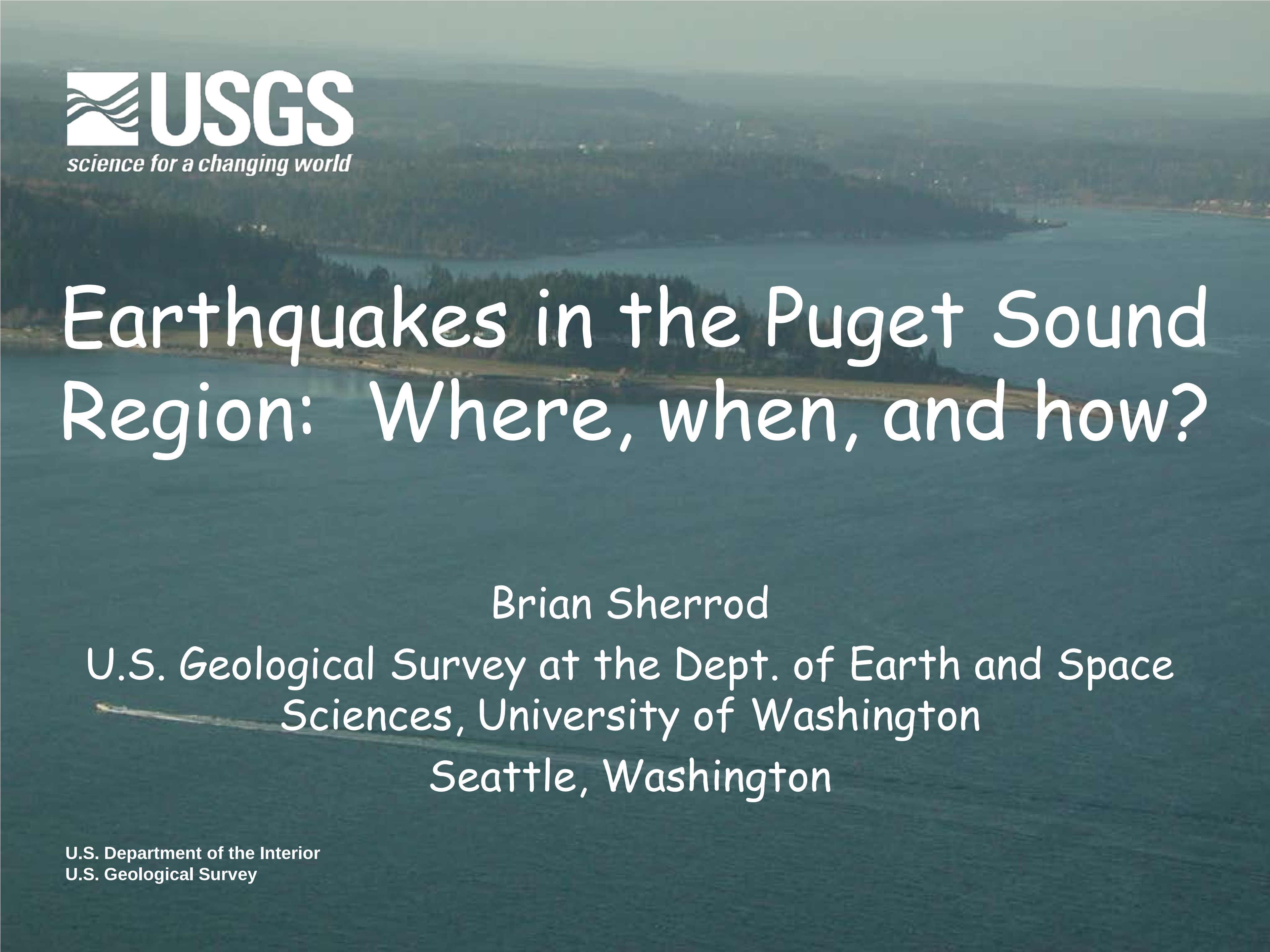


Earthquakes in the Puget Sound Region: Where, when, and how?

Brian Sherrod

U.S. Geological Survey at the Dept. of Earth and Space Sciences, University of Washington

Seattle, Washington

Outline

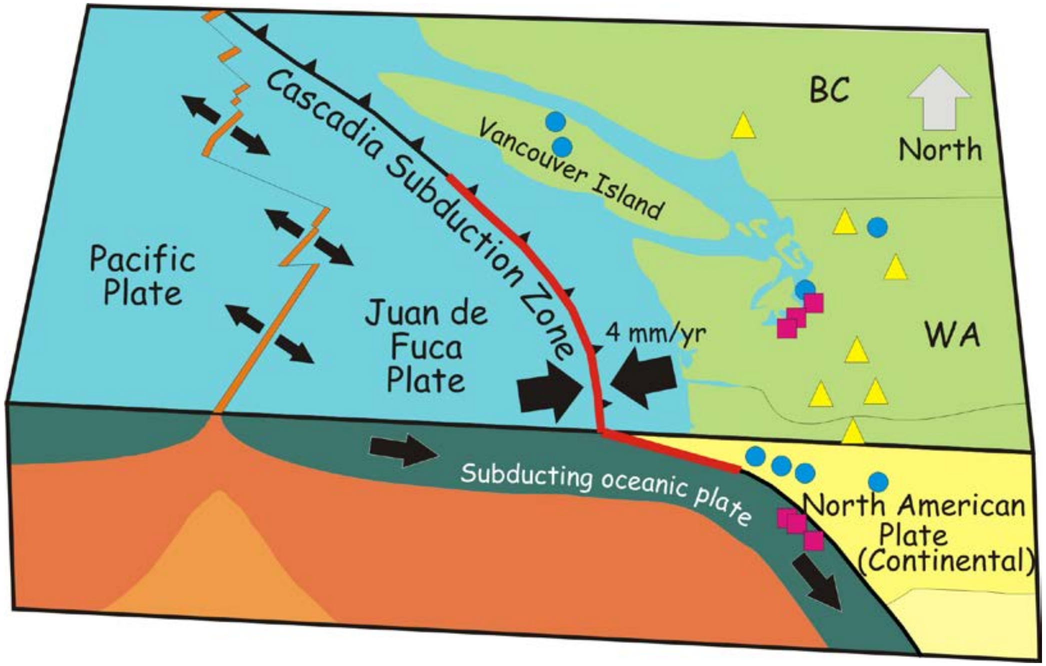
1. *What are earthquakes and faults?*
2. *How do we find faults?*
3. *What types of faults do we have here in western Washington and how do we determine if the faults we find are active?*

What are earthquakes and faults?

Earthquakes are caused by the sudden release of accumulated strain along faults, releasing energy in a series of low-frequency sound waves called seismic waves (P, S, and Surface [Love] waves).

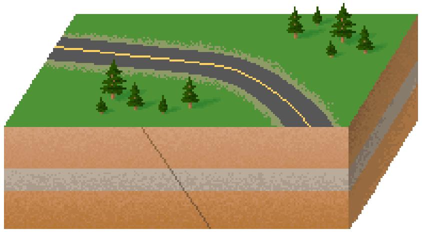
Fractures in Earth's crust, or lithosphere, where sections of rock have slipped past each other are called faults.

Three Fault Types

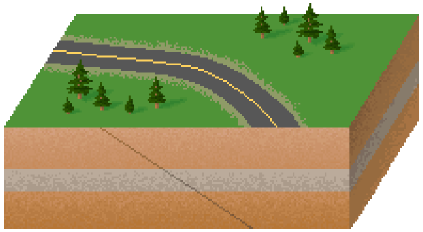


Earthquake Sources

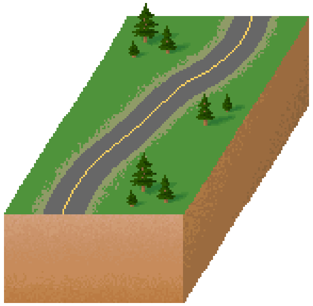
- ■ Deep earthquakes (Intraslab)
- ● Shallow earthquakes (in Nam)
- ╲ Subduction zone earthquakes
- ▲ Cascade volcano



1. Normal fault



2. Reverse fault (or thrust fault)



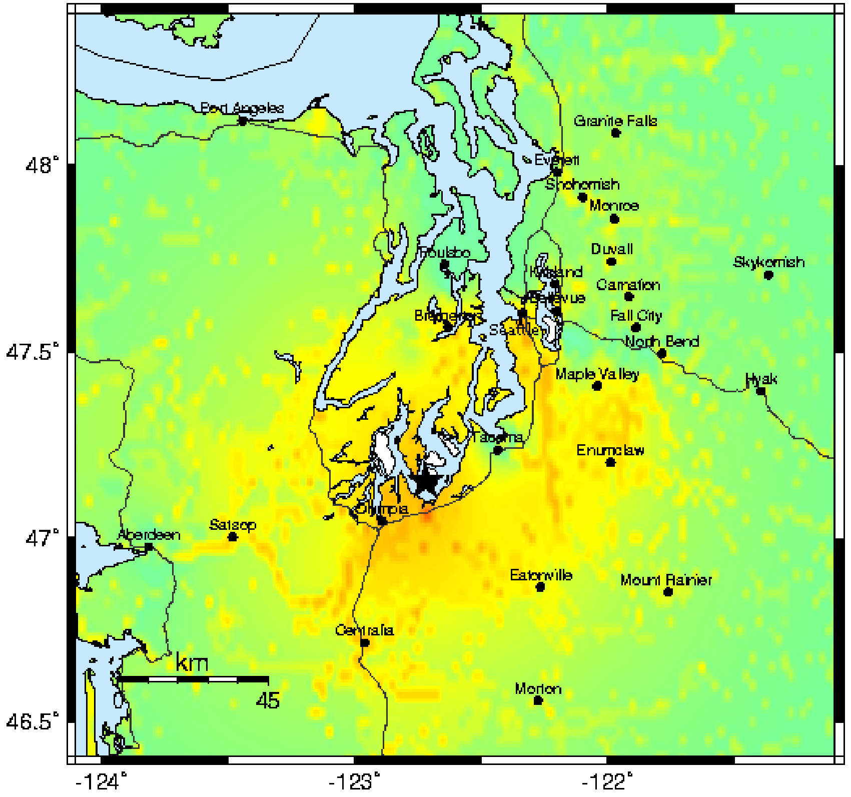
3. Transform fault

Fault scarp: a steep slope or cliff formed directly by movement along a fault and representing the exposed surface of the fault

A Tale of Two Earthquakes: Effect of Hypocentral Depth on Shaking

Mw 6.8 Nisqually Earthquake
Depth = 52 km

PNSN Rapid Instrumental Intensity Map Epicenter: 17.6 km NE of Olympia, WA
Wed Feb 26, 2001 10:54:00 AM PST M 6.8 N47.15 W122.72 ID:0102261654

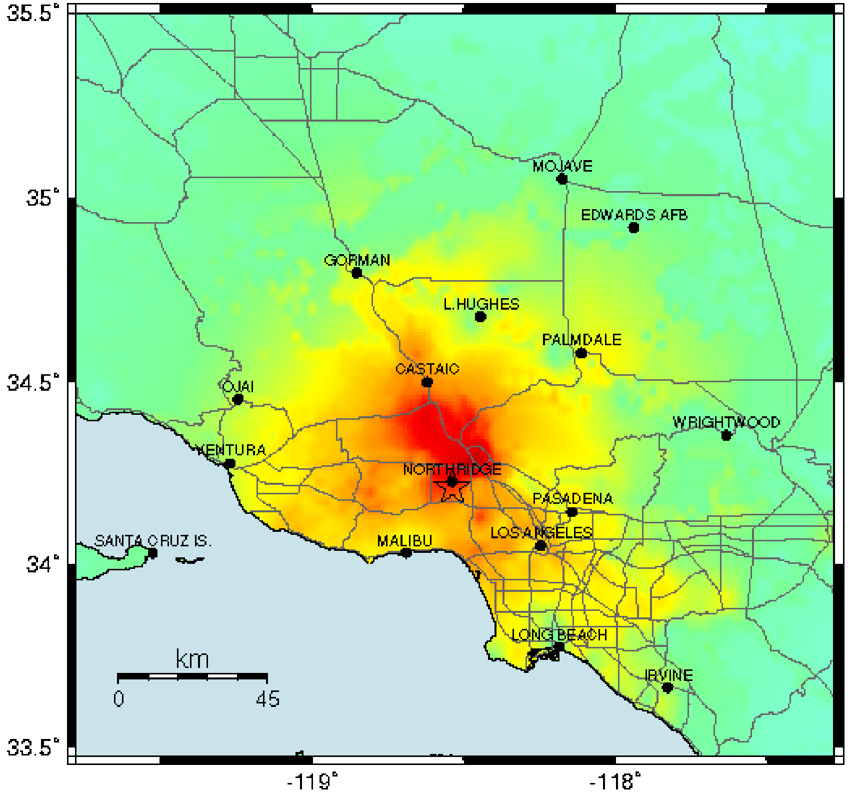


PROCESSED: Mon Mar 5, 2001 06:32:25 PM PST,

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

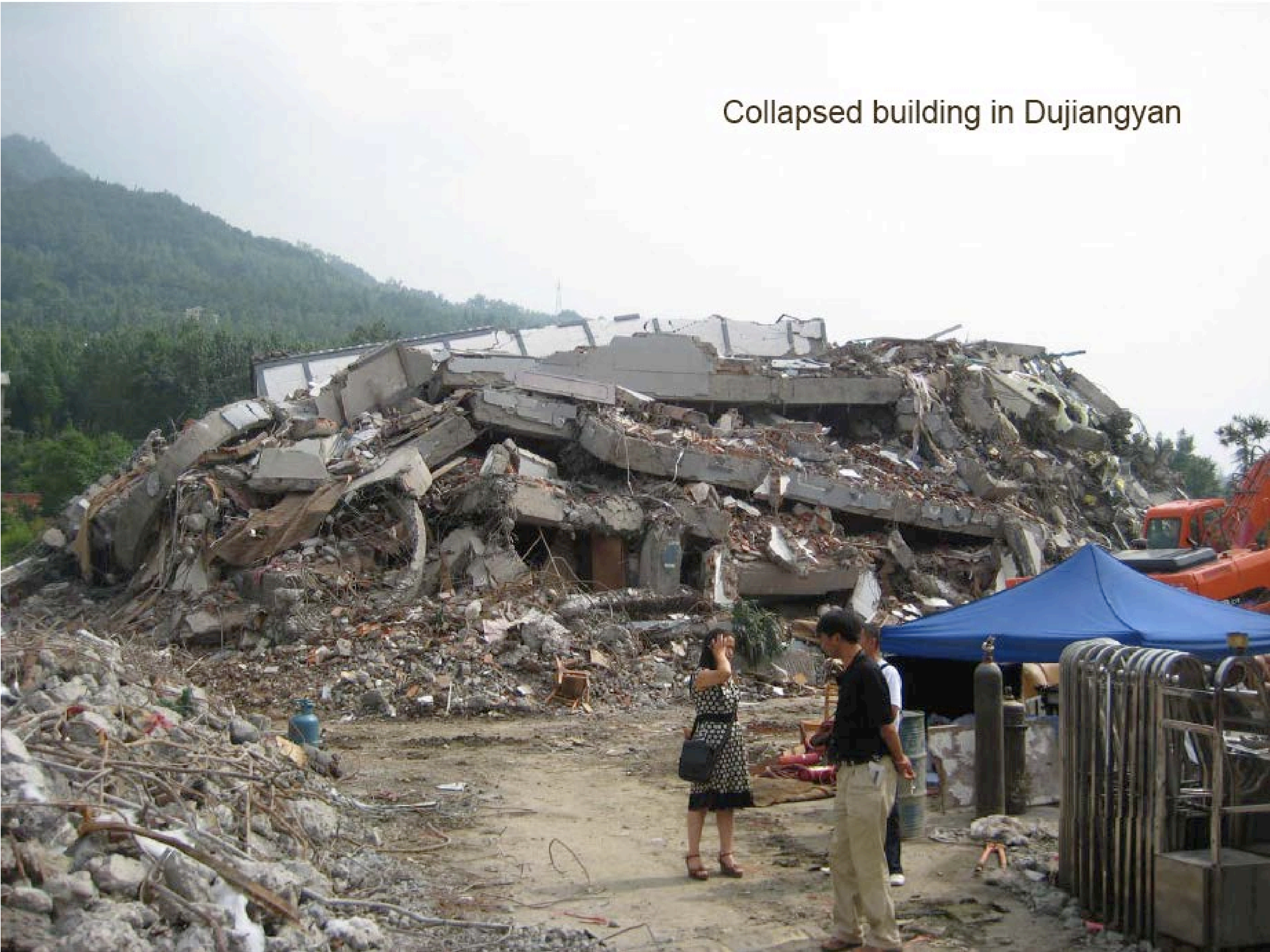
Mw 6.7 Northridge Earthquake
Depth = 18 km

TriNet Rapid Instrumental Intensity Map for Northridge Earthquake
Mon Jan 17, 1994 04:30:55 AM PST M 6.7 N34.21 W118.54 ID:Northridge

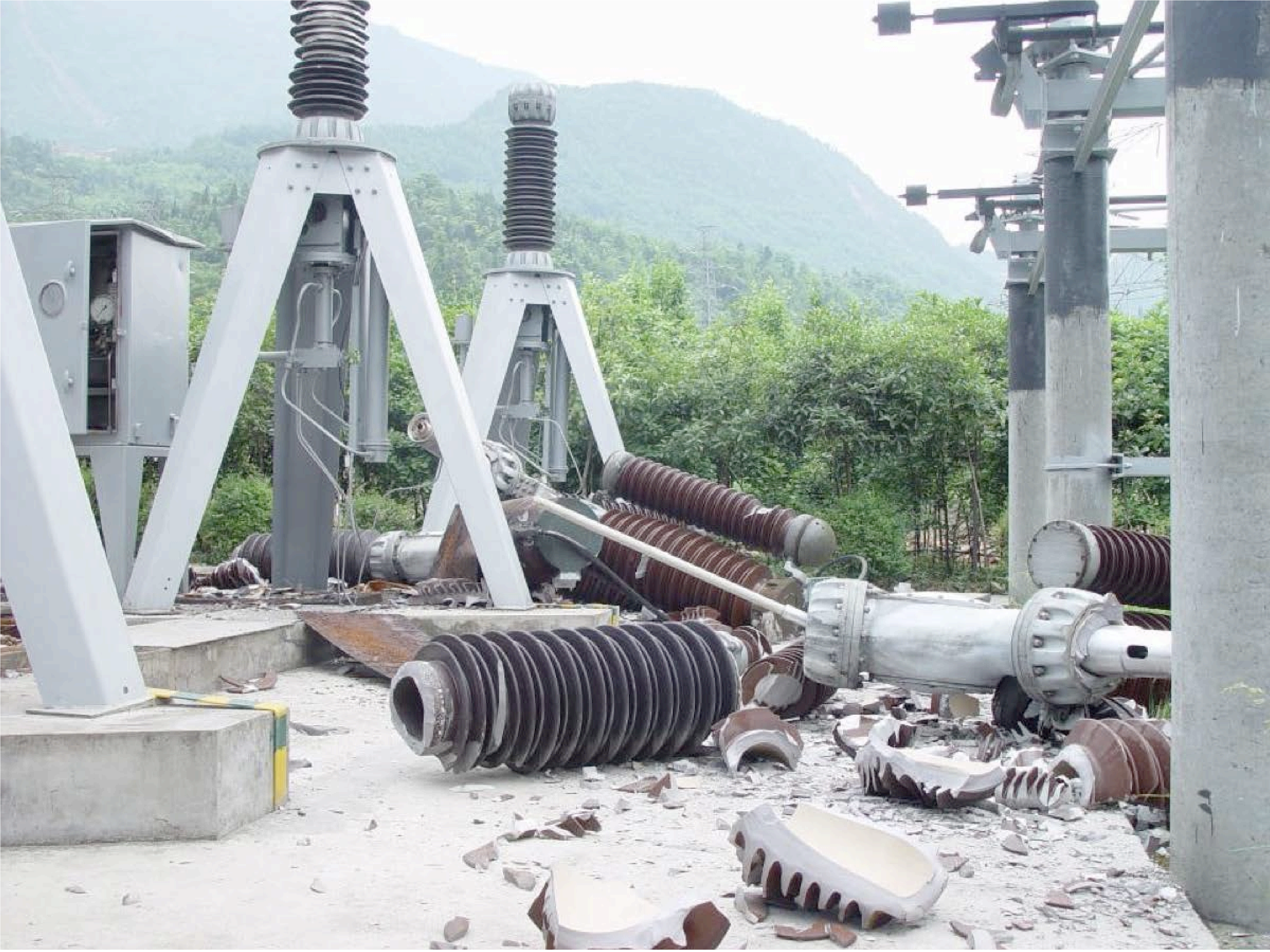


PROCESSED: Tue Mar 6, 2001 11:35:21 AM PST,

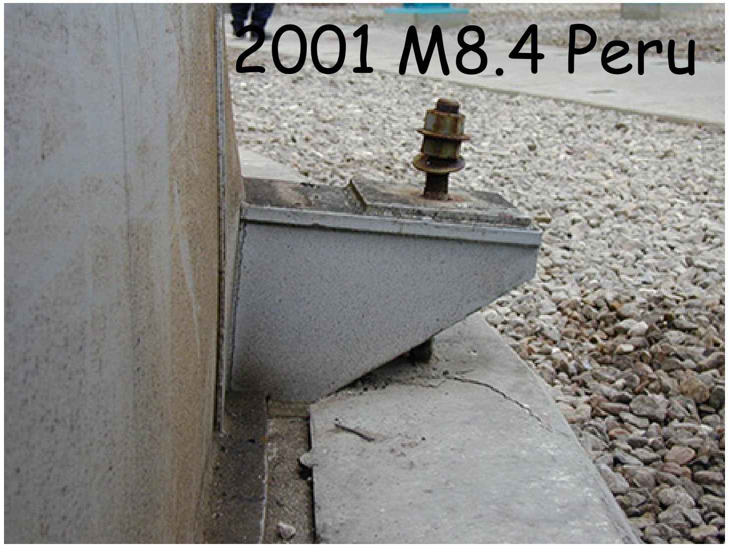
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+



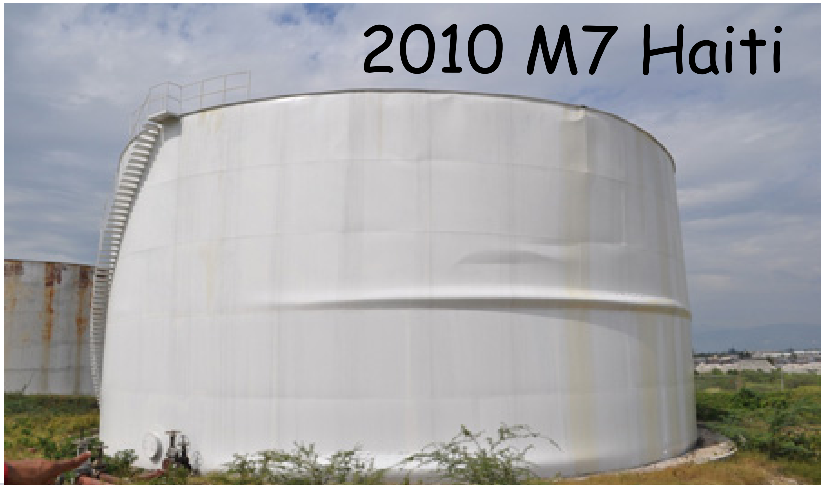
Collapsed building in Dujiangyan



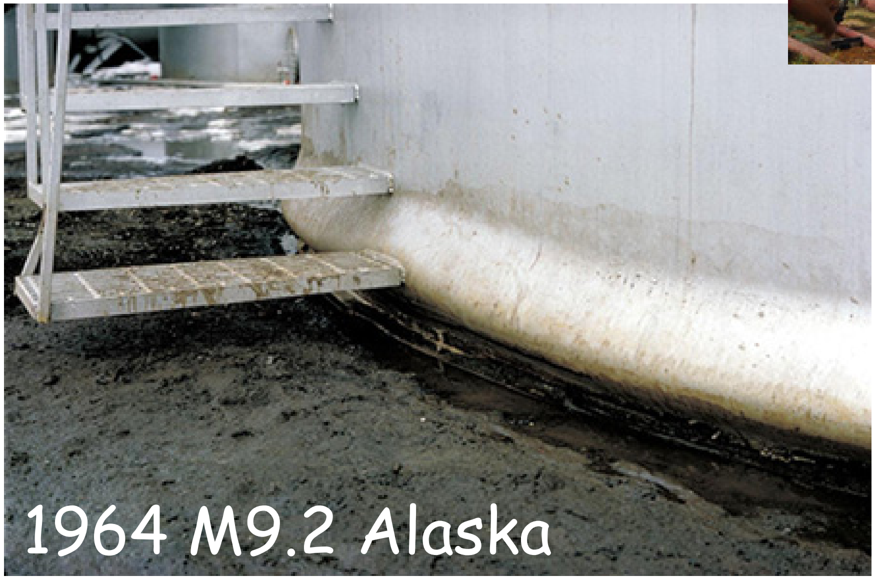
Earthquake damage to water tanks in recent earthquakes



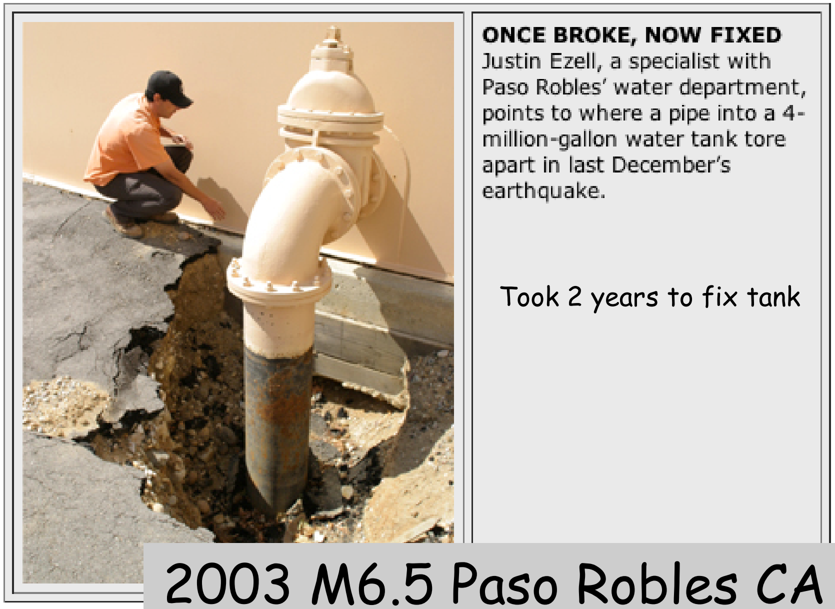
2001 M8.4 Peru



2010 M7 Haiti



1964 M9.2 Alaska

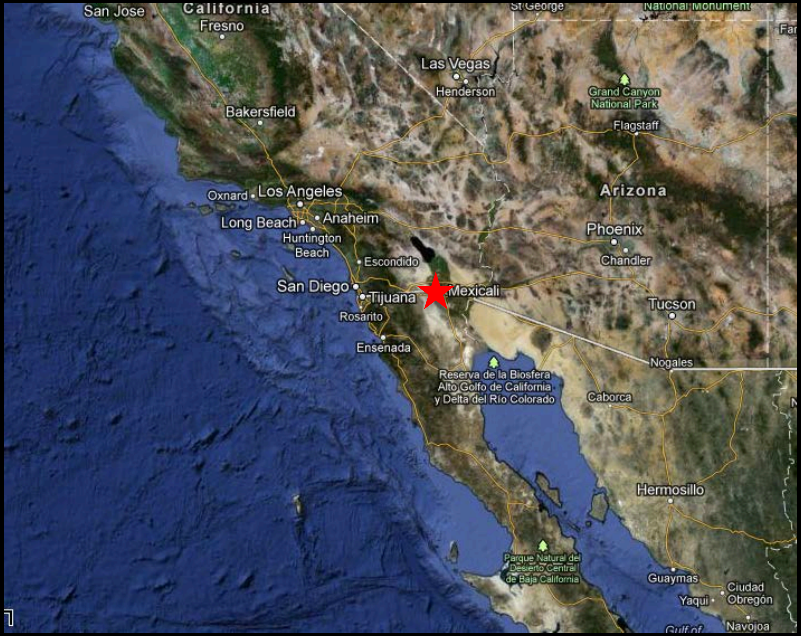


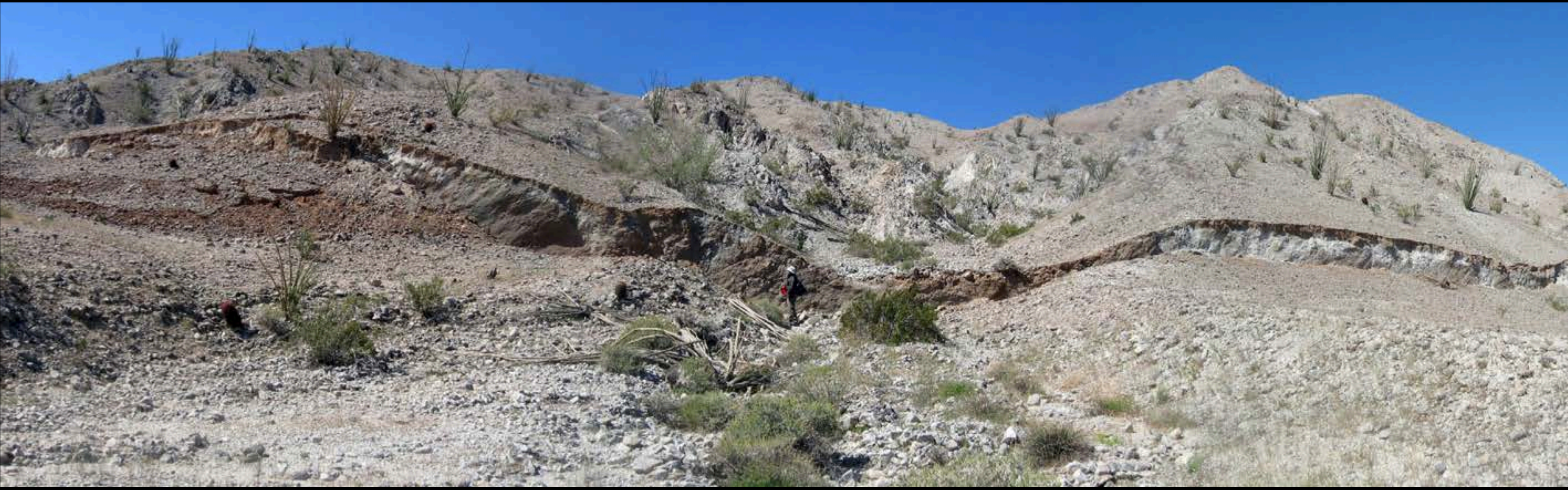
ONCE BROKE, NOW FIXED Justin Ezell, a specialist with Paso Robles' water department, points to where a pipe into a 4-million-gallon water tank tore apart in last December's earthquake.

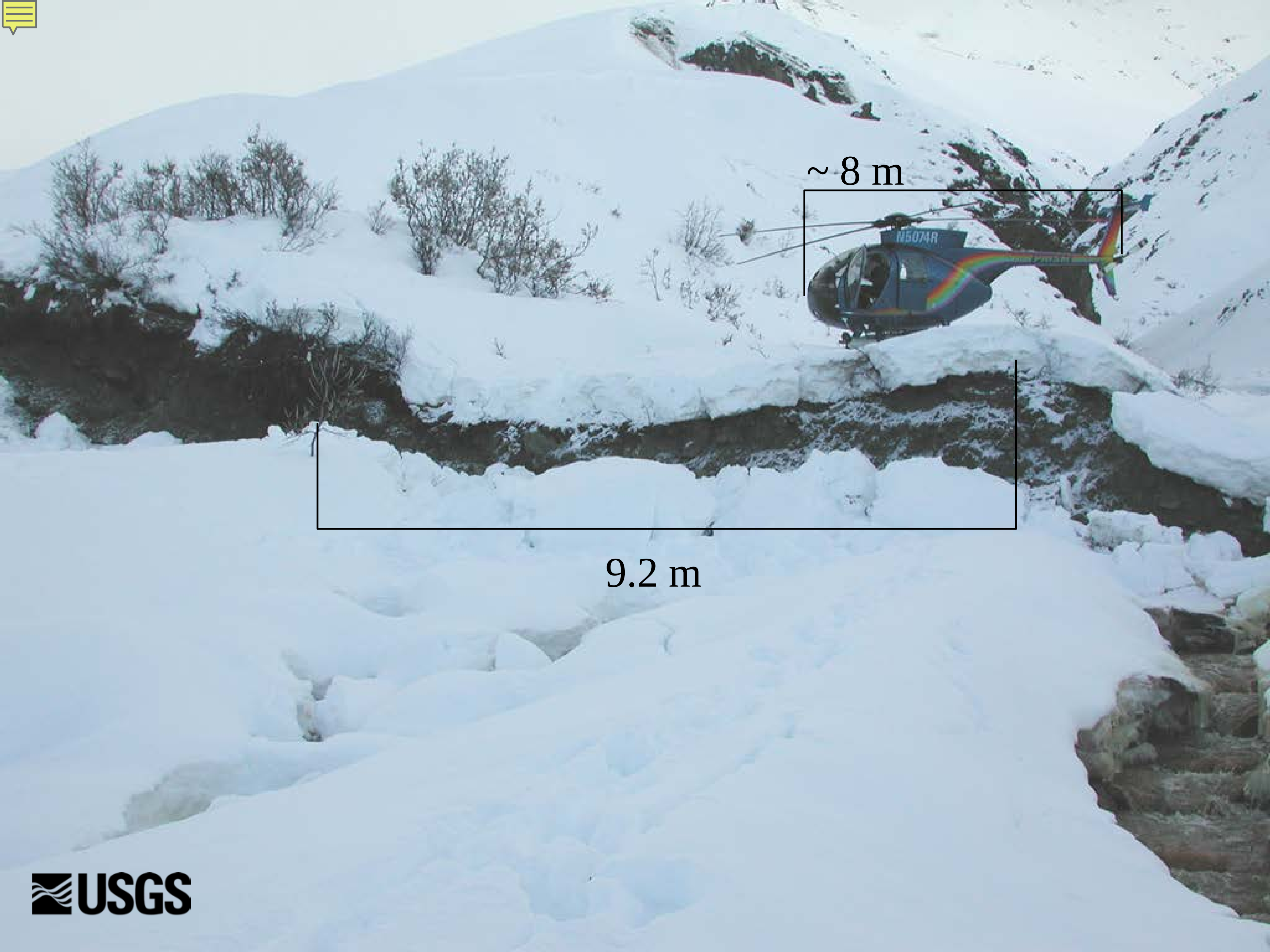
Took 2 years to fix tank

2003 M6.5 Paso Robles CA

Mw 7.2 El Mayor Cucapah (Baja California) Earthquake of April 4, 2010

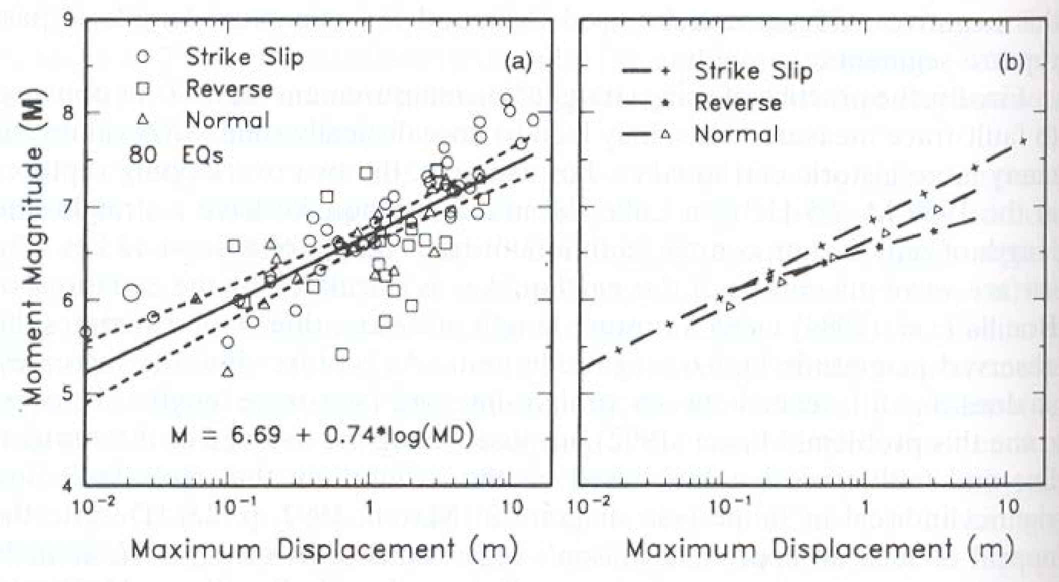


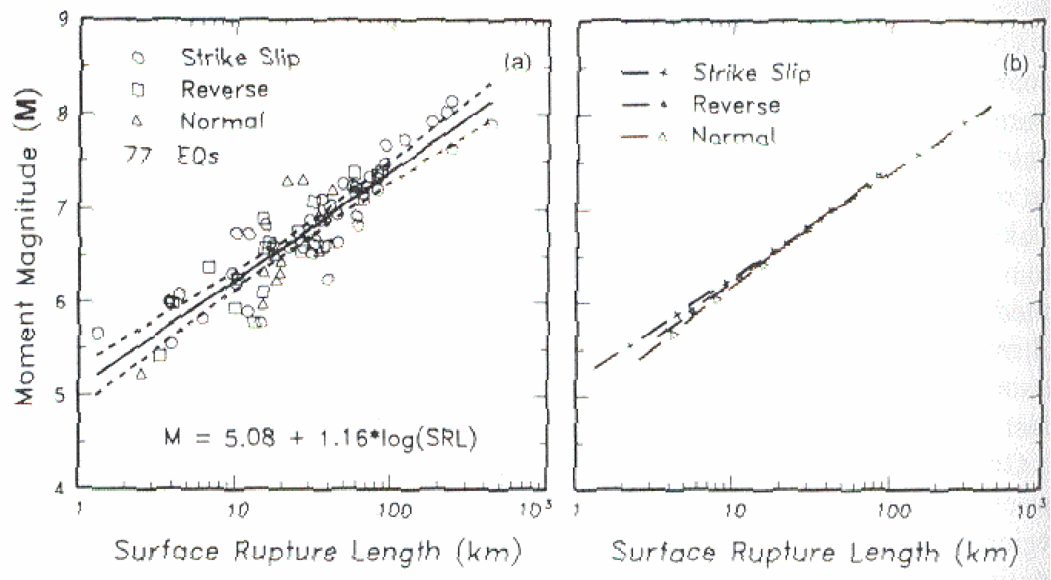


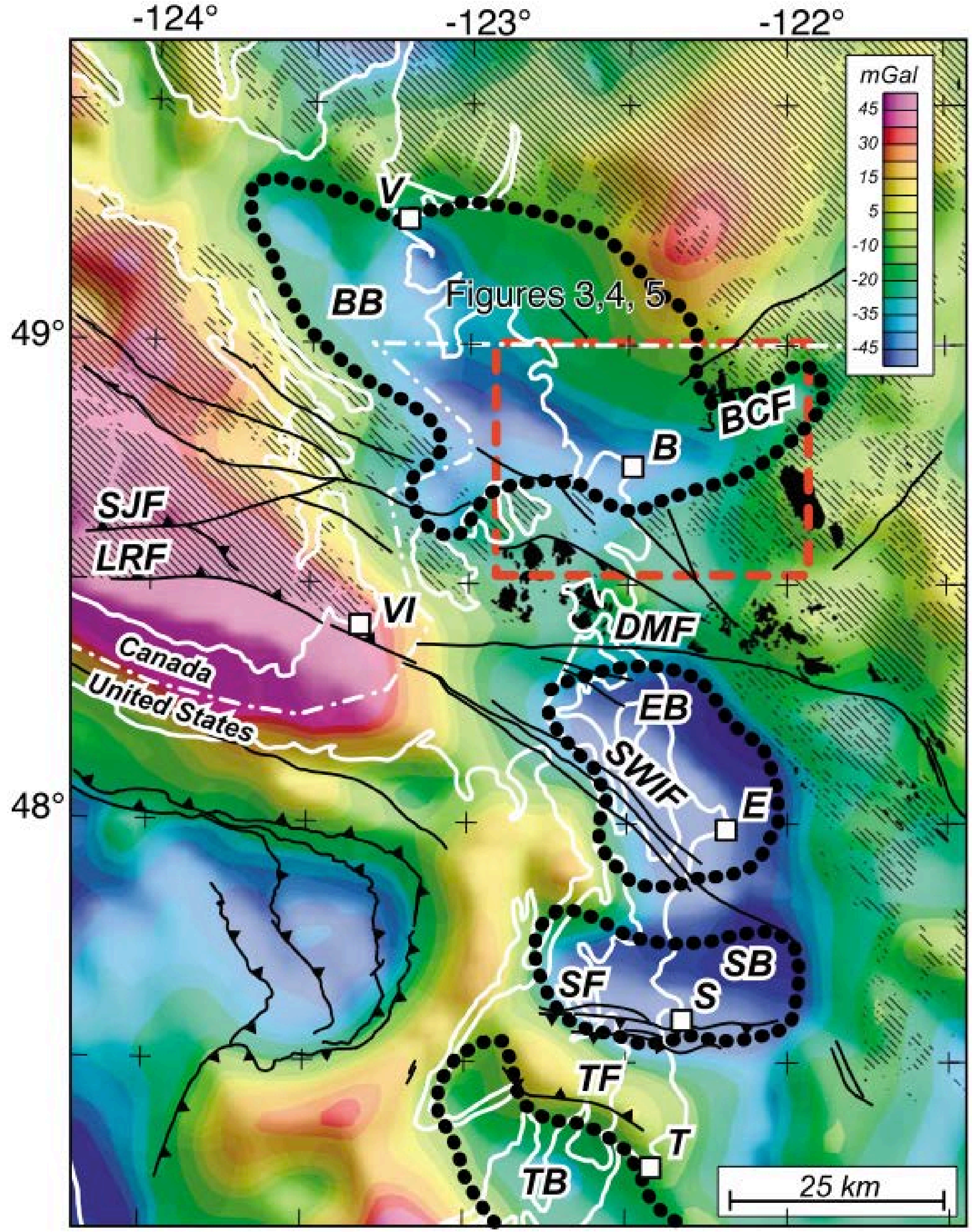

~ 8 m
N5074R
9.2 m

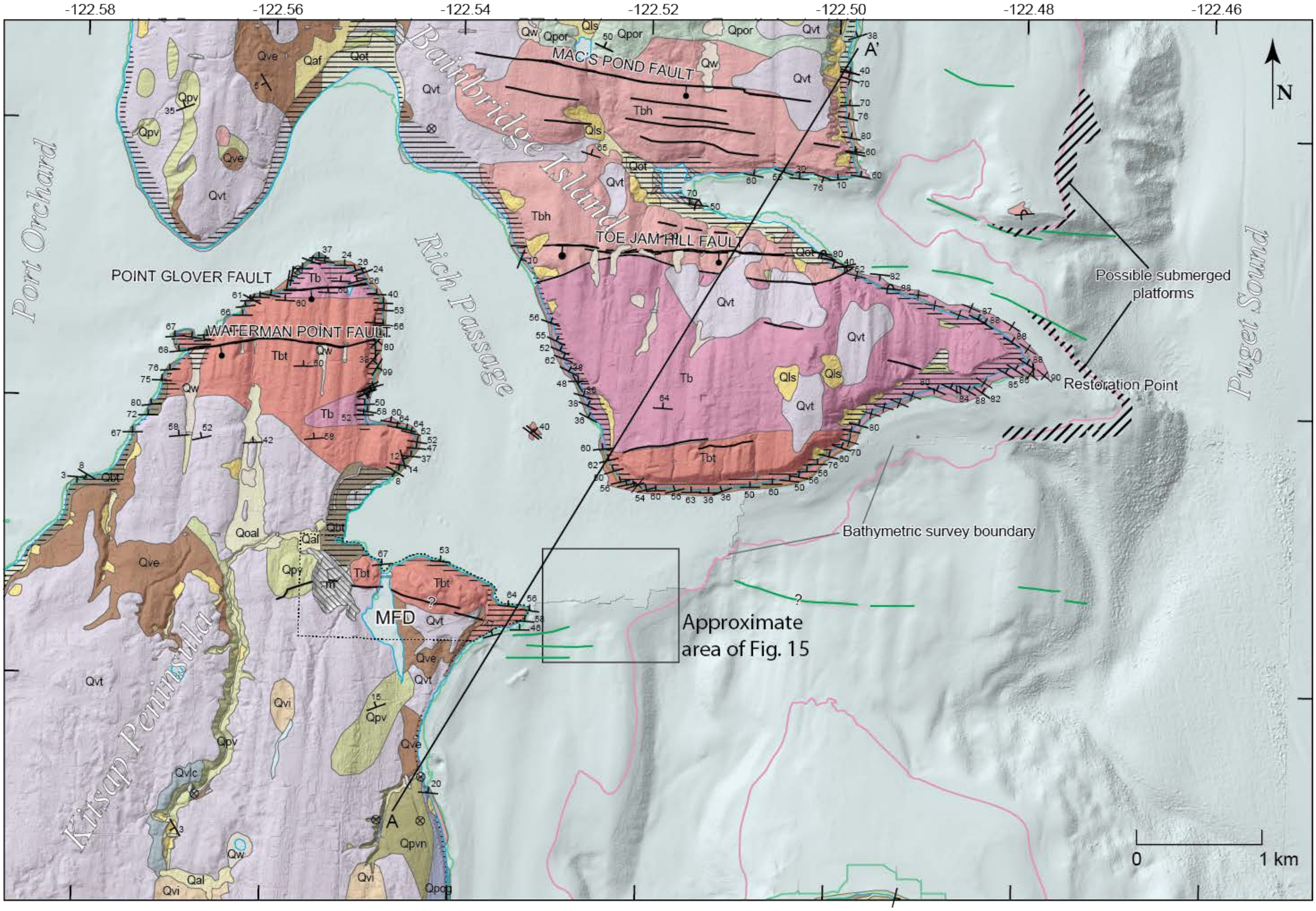
How do we find faults?

… or better yet, why bother looking for them?

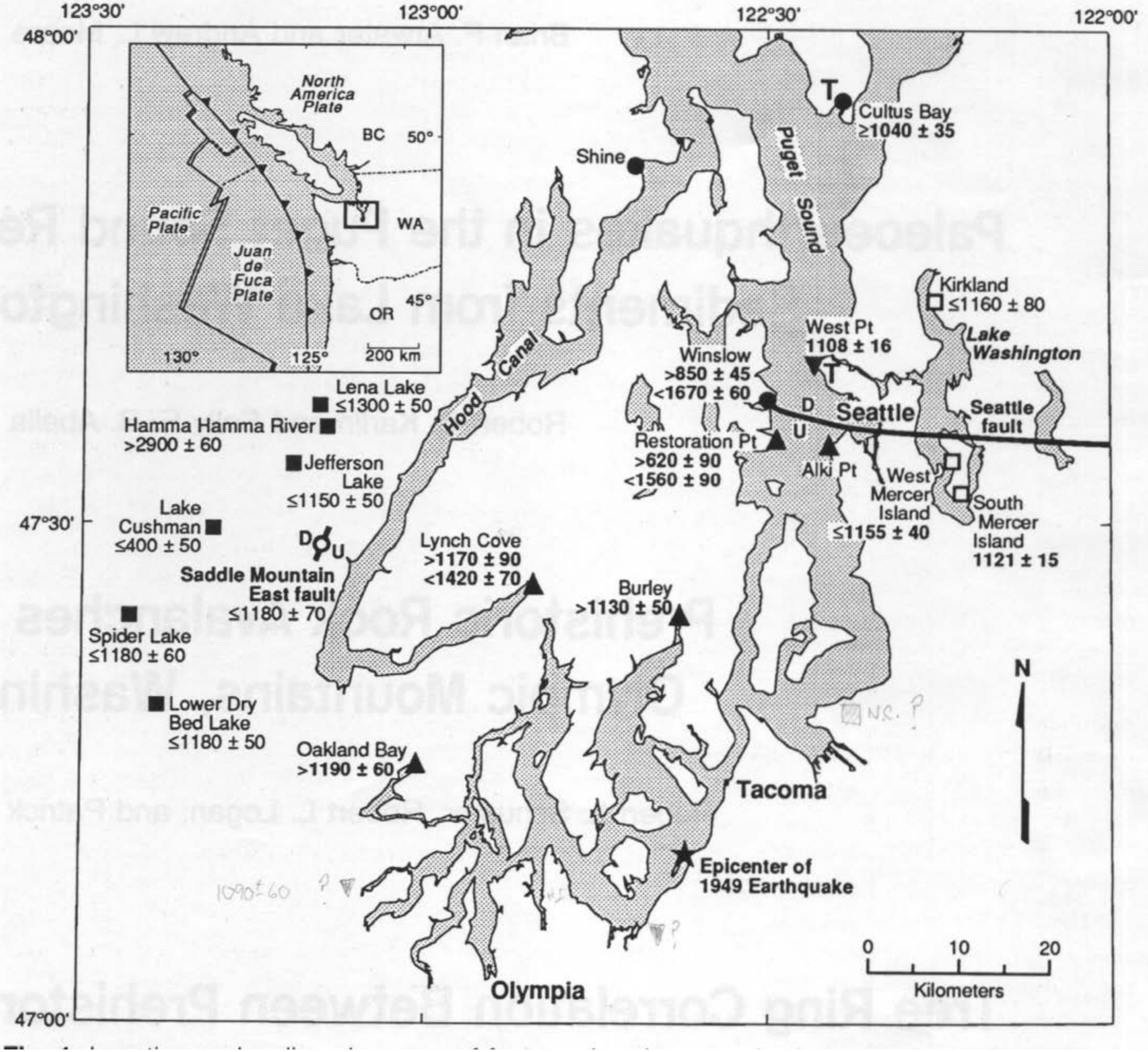





-124°
-123°
-122°
49°
48°
mGal
45
30
15
5
-10
-20
-35
-45
V
BB
Figures 3,4, 5
BCF
B
SJF
LRF
VI
DMF
Canada
United States
EB
SWIF
E
SB
SF
S
TF
T
TB
25 km

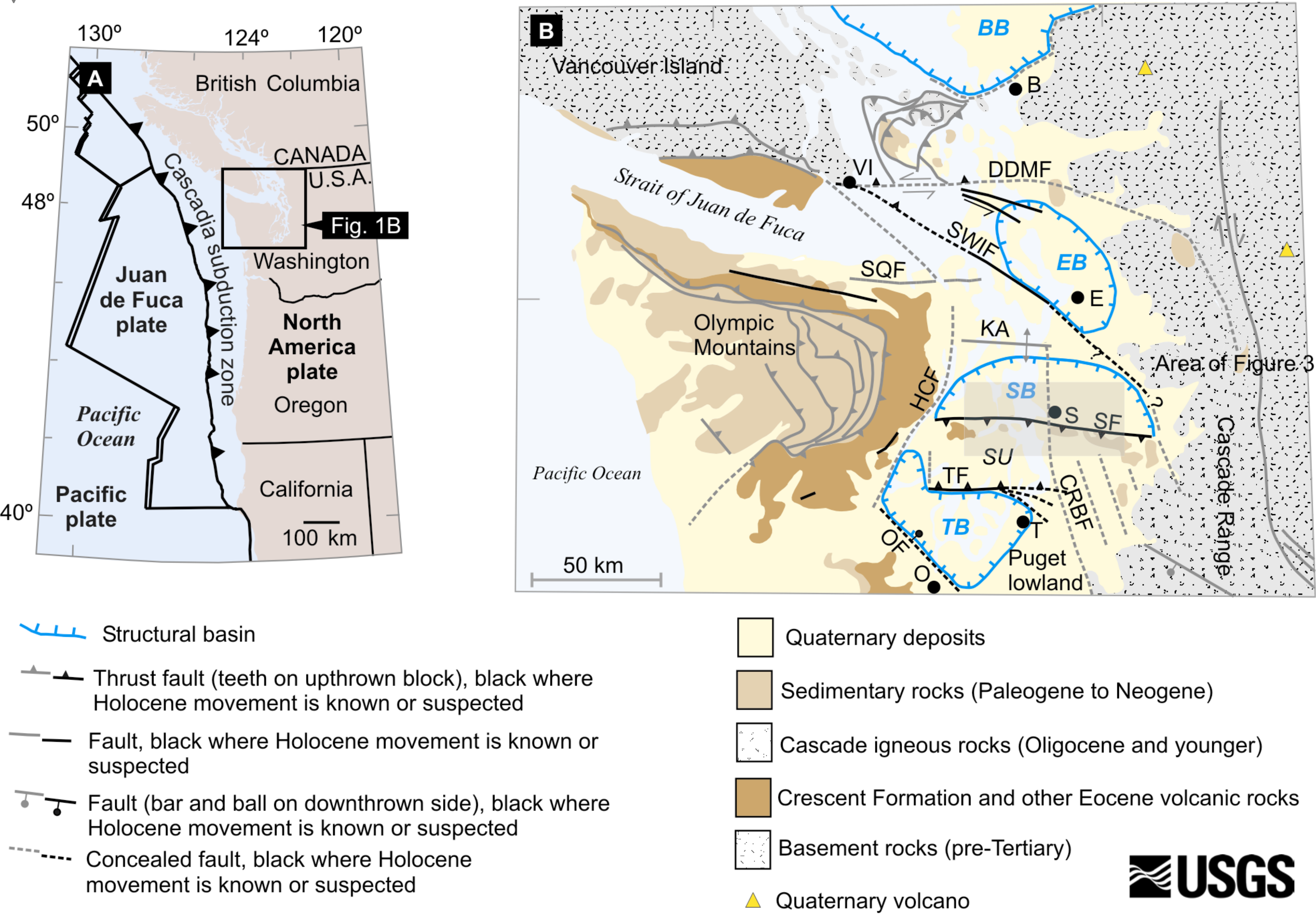


-122.58
-122.56
-122.54
-122.52
-122.50
-122.48
-122.46
47.60
47.58
47.56
N
Port Orchard
Bainbridge Island
Rich Passage
Puget Sound
Kitsap Peninsula
MAC'S POND FAULT
TOE JAM HILL FAULT
POINT GLOVER FAULT
WATERMAN POINT FAULT
Restoration Point
Possible submerged platforms
Bathymetric survey boundary
Approximate area of Fig. 15
MFD
A
A'
Qve
Qaf
Qot
Qvt
Qpv
Qw
Qls
Qpor
Tbh
Tb
Tbt
Qbt
Qoal
Qal
Qvi
Qvlc
Qpvn
Qpog
m
?
0
1 km

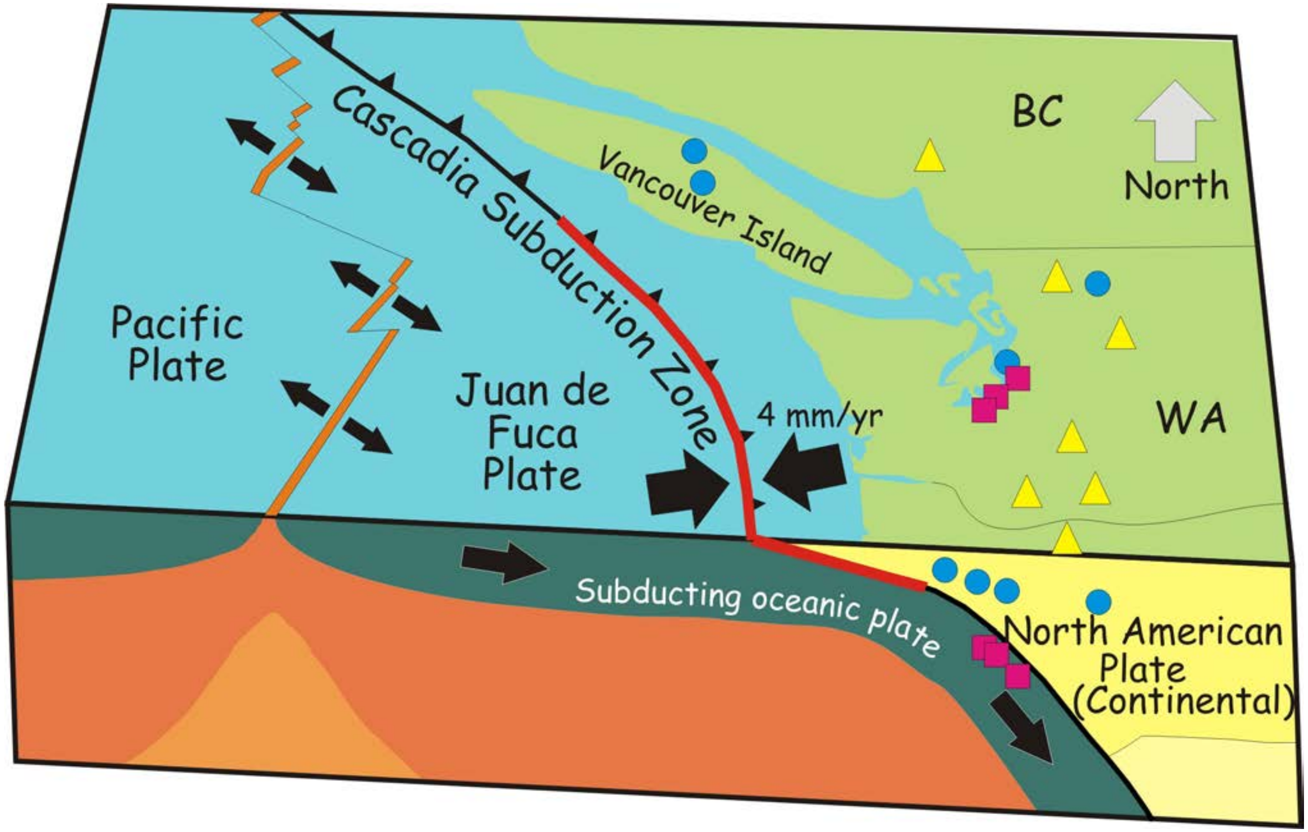


USGS

(from Bucknam et al., Science, vol. 258, 1992)


A
130º
124º
120º
50º
48º
40º
British Columbia
CANADA
U.S.A.
Fig. 1B
Washington
Cascadia subduction zone
Juan de Fuca plate
North America plate
Oregon
Pacific Ocean
Pacific plate
California
100 km
B
Vancouver Island
BB
B
VI
DDMF
Strait of Juan de Fuca
SWIF
EB
E
SQF
KA
Olympic Mountains
Area of Figure 3
HCF
SB
S
SF
?
SU
TF
CRBF
TB
T
OF
O
Puget lowland
Cascade Range
Pacific Ocean
50 km
Structural basin
Thrust fault (teeth on upthrown block), black where Holocene movement is known or suspected
Fault, black where Holocene movement is known or suspected
Fault (bar and ball on downthrown side), black where Holocene movement is known or suspected
Concealed fault, black where Holocene movement is known or suspected
Quaternary deposits
Sedimentary rocks (Paleogene to Neogene)
Cascade igneous rocks (Oligocene and younger)
Crescent Formation and other Eocene volcanic rocks
Basement rocks (pre-Tertiary)
Quaternary volcano
USGS

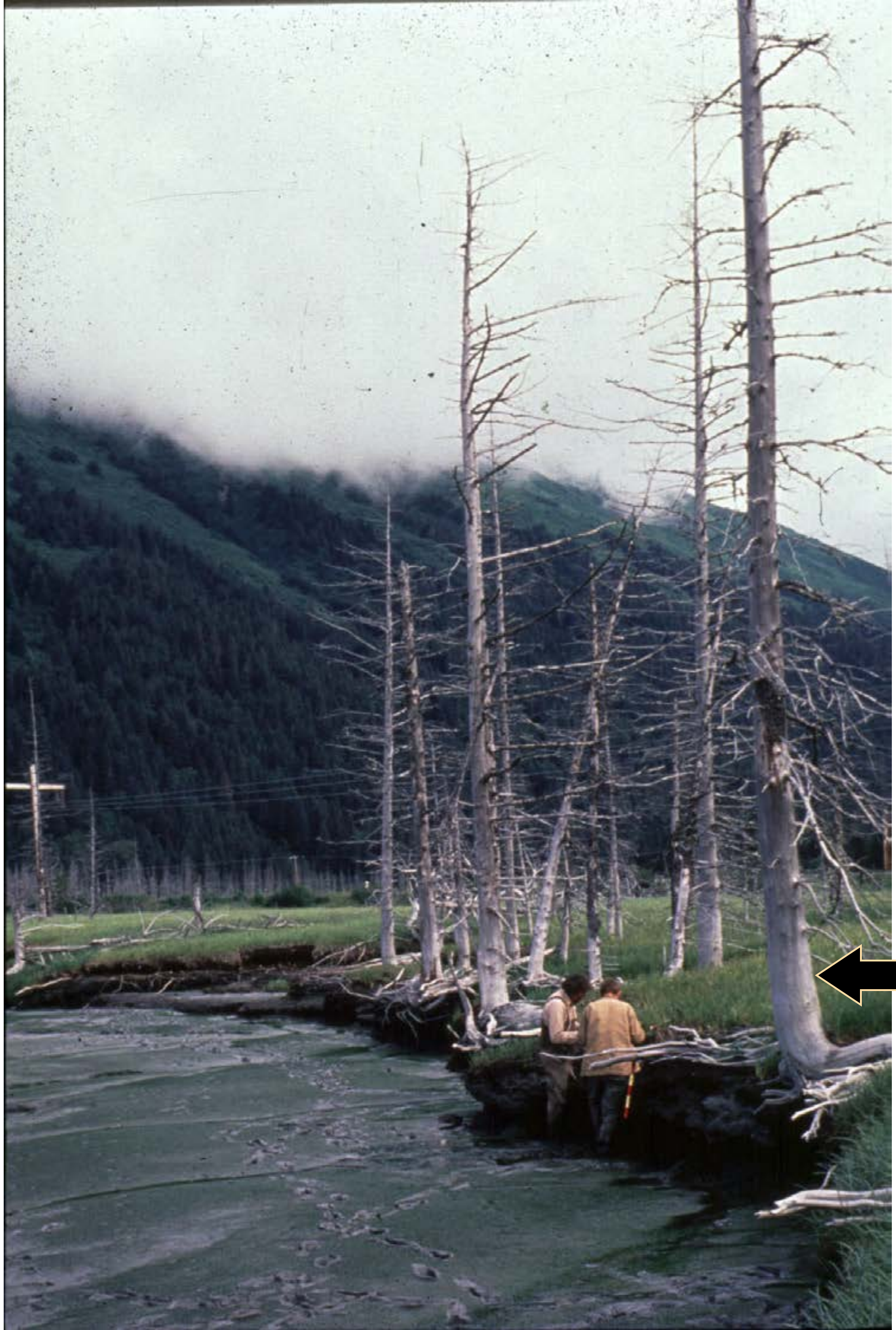
What types of faults do we have here in western Washington and how do we determine if the faults we find are active?



Earthquake Sources

- ■ Deep earthquakes (Intraslab)
- ● Shallow earthquakes (in Nam)
- ╲ Subduction zone earthquakes

- △ Cascade volcano



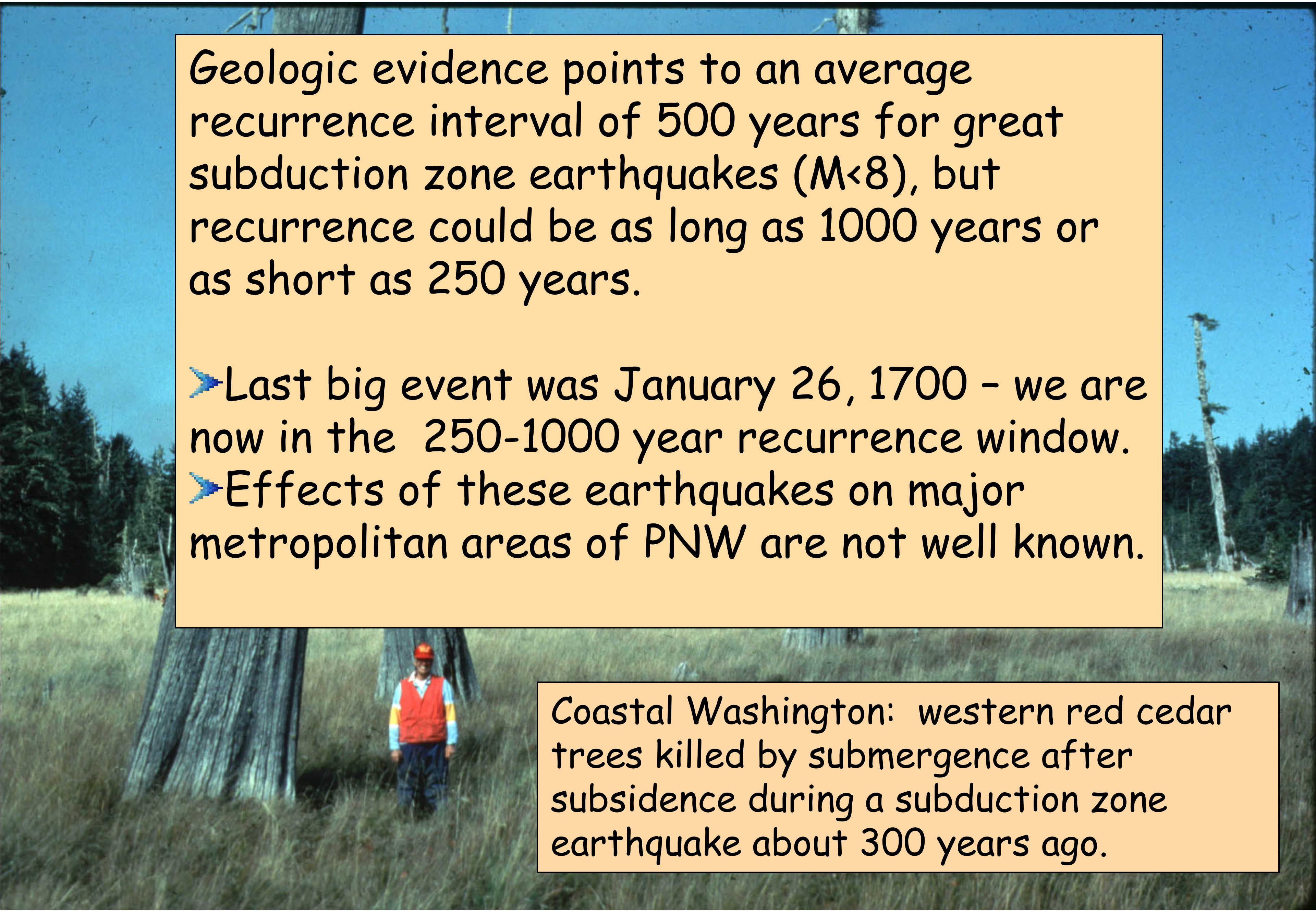
Lesson from 1964 Alaska Earthquake:

Areas of the coastline subside during great subduction zone earthquakes ($M_w > 8.0$).

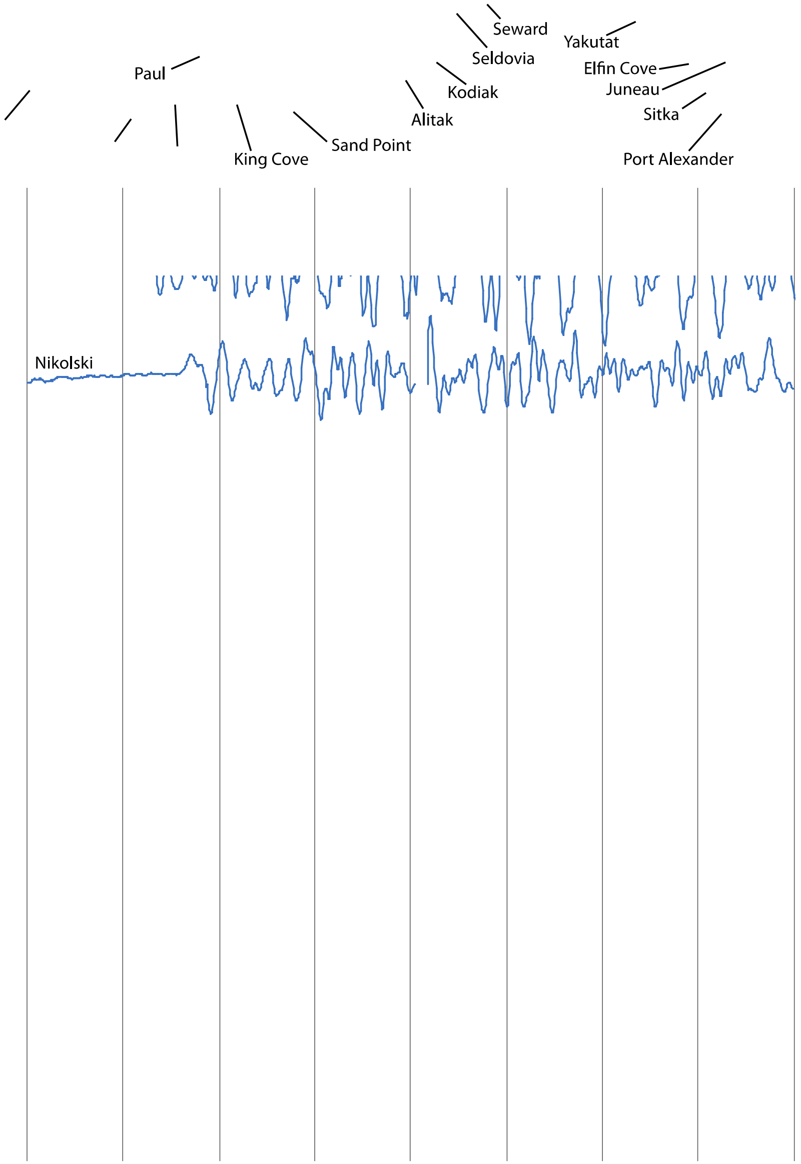
Spruce trees killed when saltwater flooded forest after subsidence lowered them into the intertidal zone

Geologic evidence points to an average recurrence interval of 500 years for great subduction zone earthquakes (M<8), but recurrence could be as long as 1000 years or as short as 250 years.

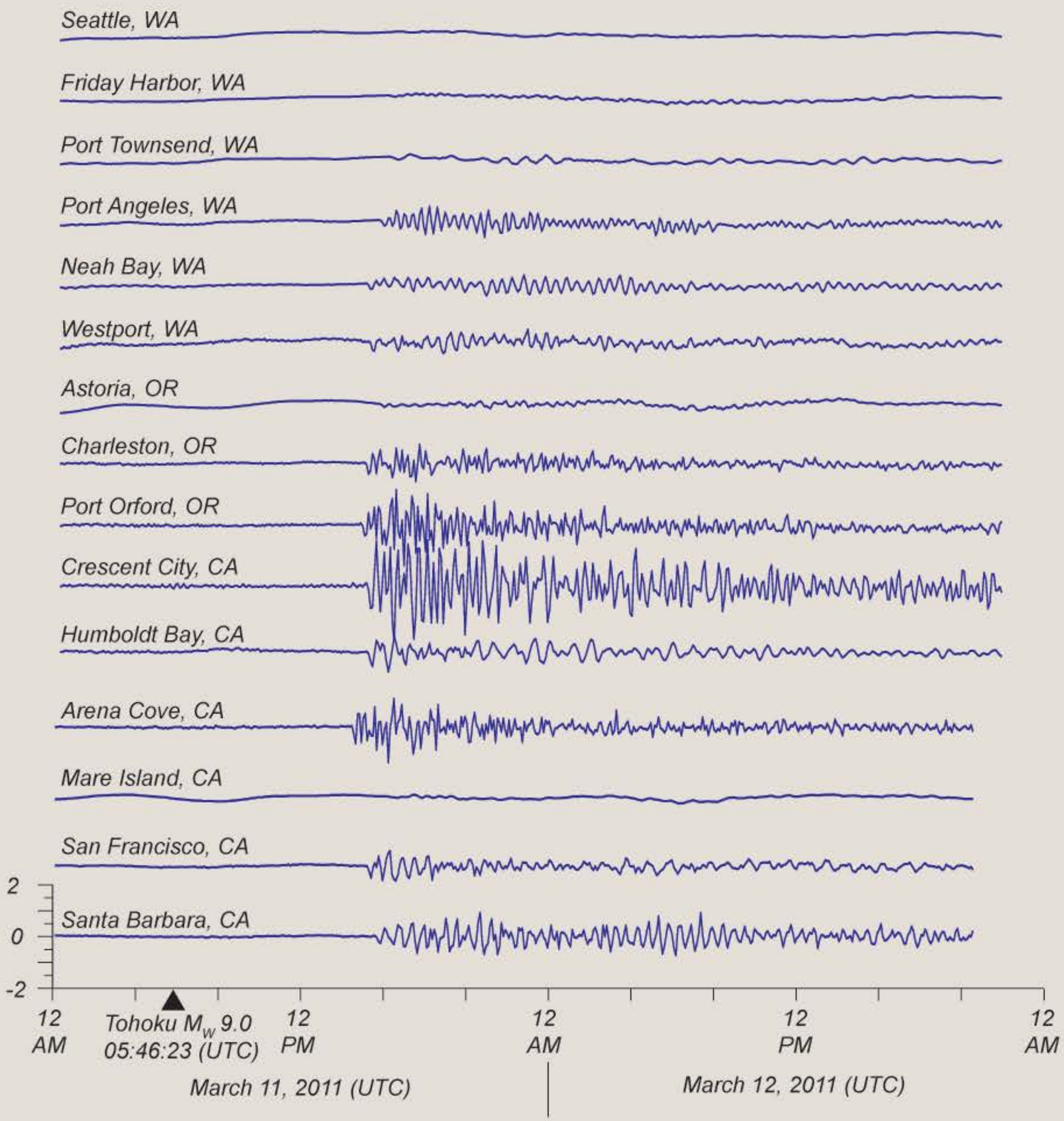
- Last big event was January 26, 1700 – we are now in the 250-1000 year recurrence window.
- Effects of these earthquakes on major metropolitan areas of PNW are not well known.

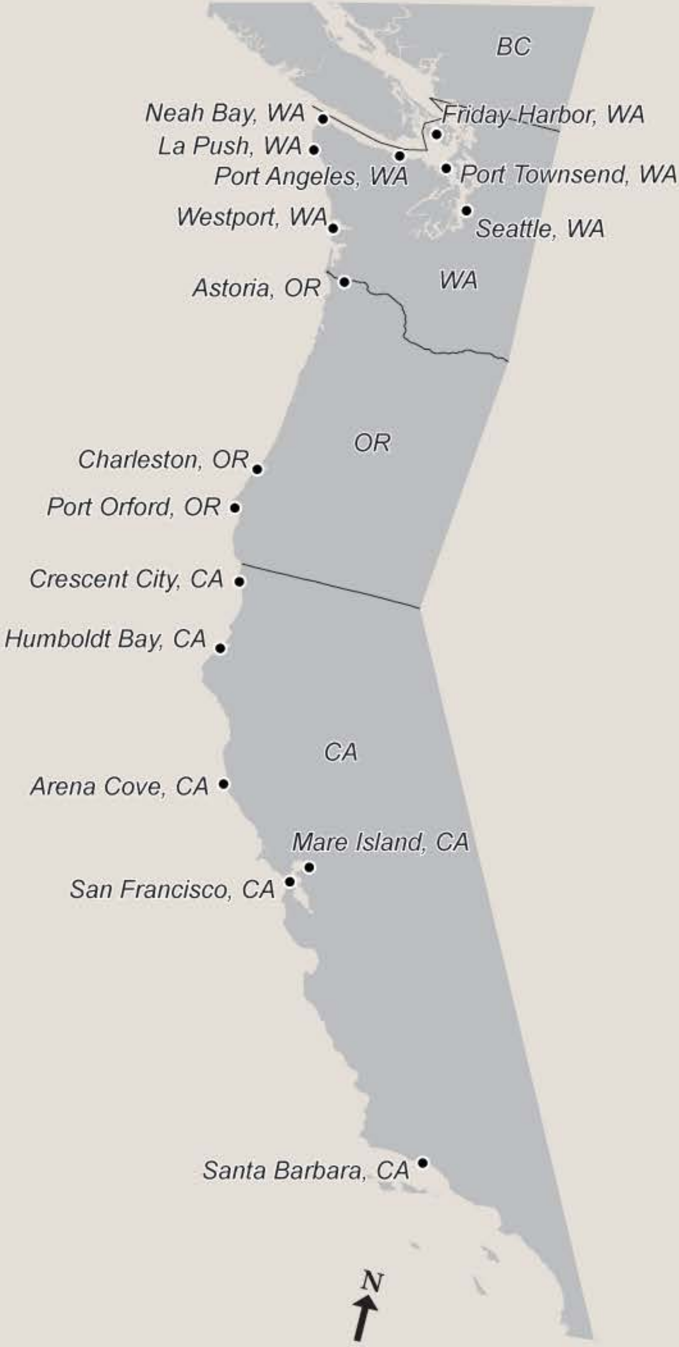


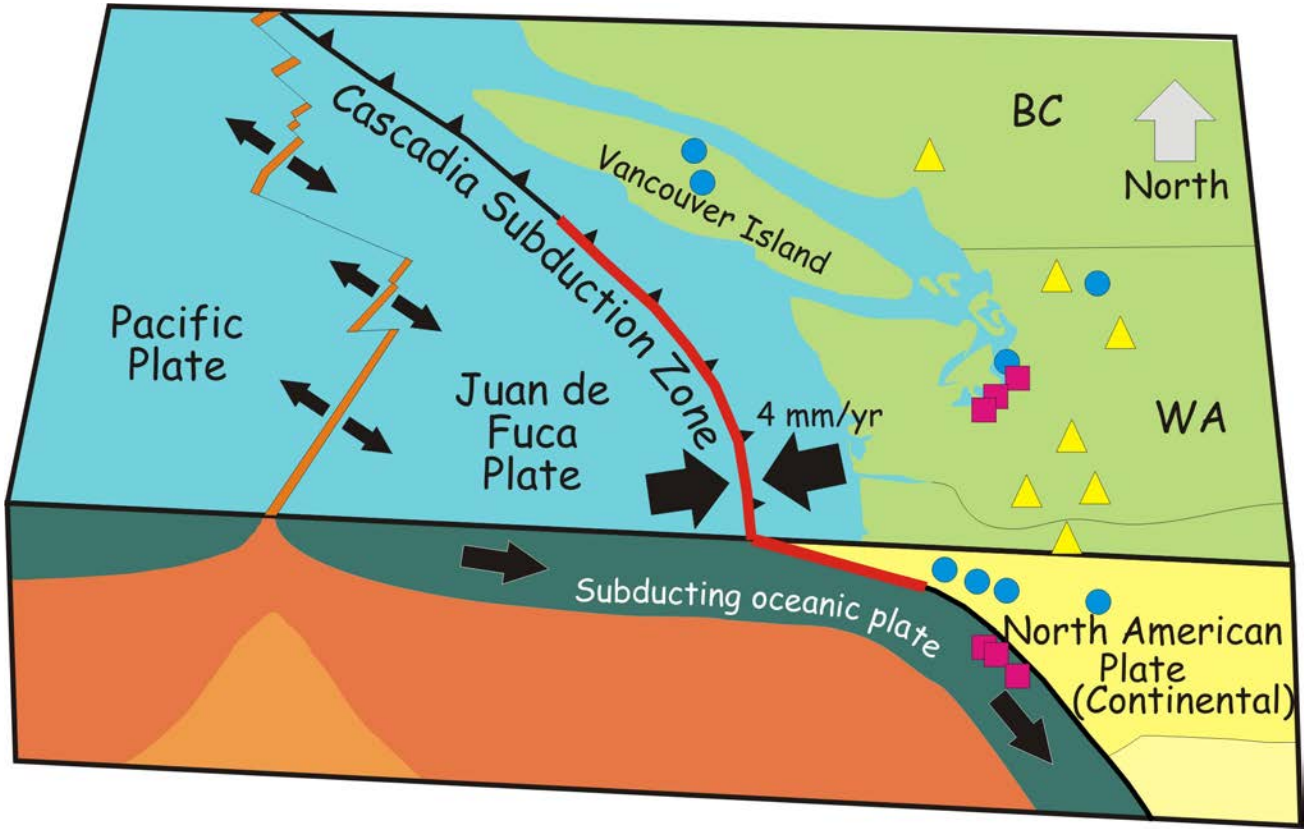
Coastal Washington: western red cedar trees killed by submergence after subsidence during a subduction zone earthquake about 300 years ago.


Seward
Seldovia
Yakutat
Paul
Elfin Cove
Kodiak
Juneau
Alitak
Sitka
Sand Point
King Cove
Port Alexander
Nikolski

March 11, 2011 Tohoku tsunami on U.S. west coast







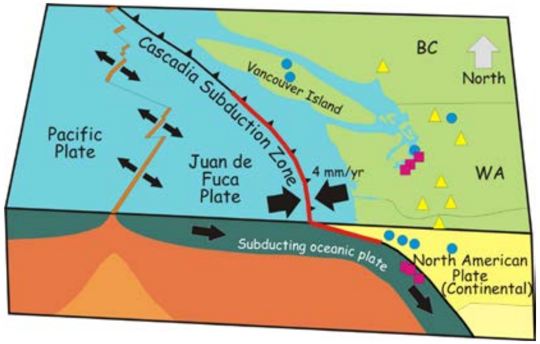
Earthquake Sources

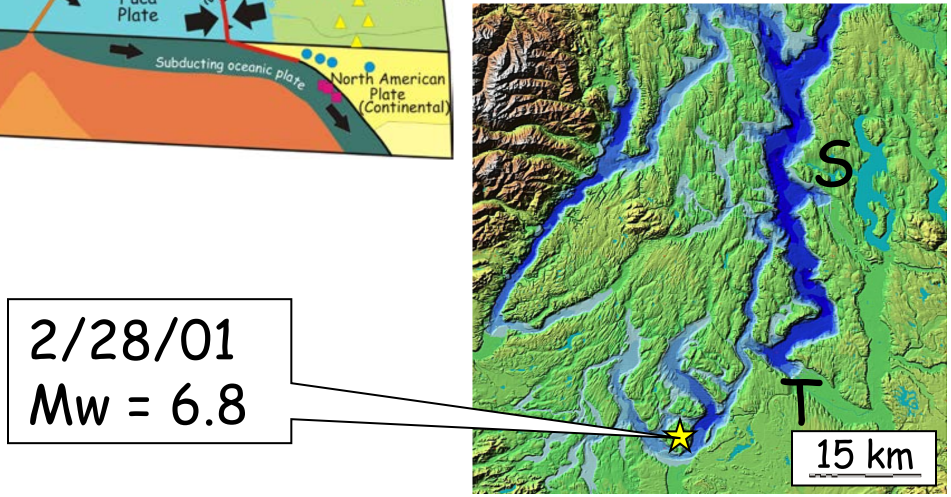
- ■ Deep earthquakes (Intraslab)
- ● Shallow earthquakes (in Nam)
- ╲ Subduction zone earthquakes

- ▲ Cascade volcano

Nisqually Earthquake

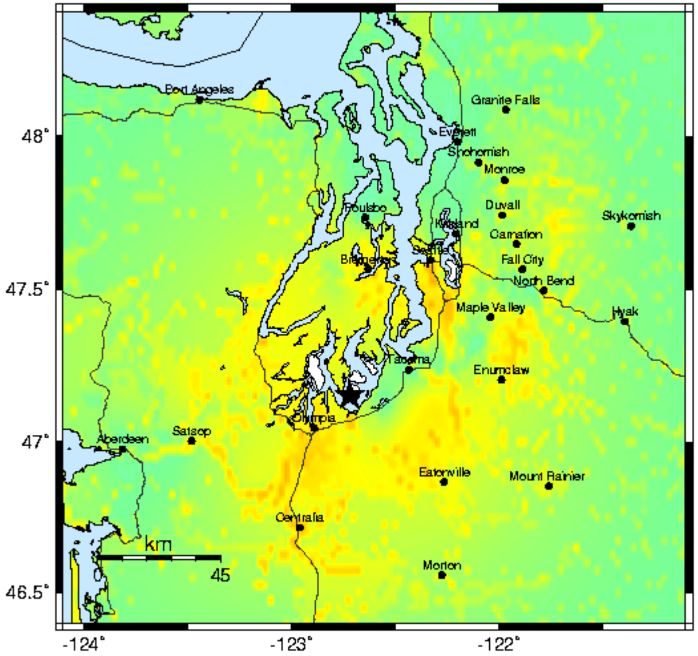
- Mw = 6.8
- Depth = 52.4 km (32.5 miles)
- Intraslab normal fault event





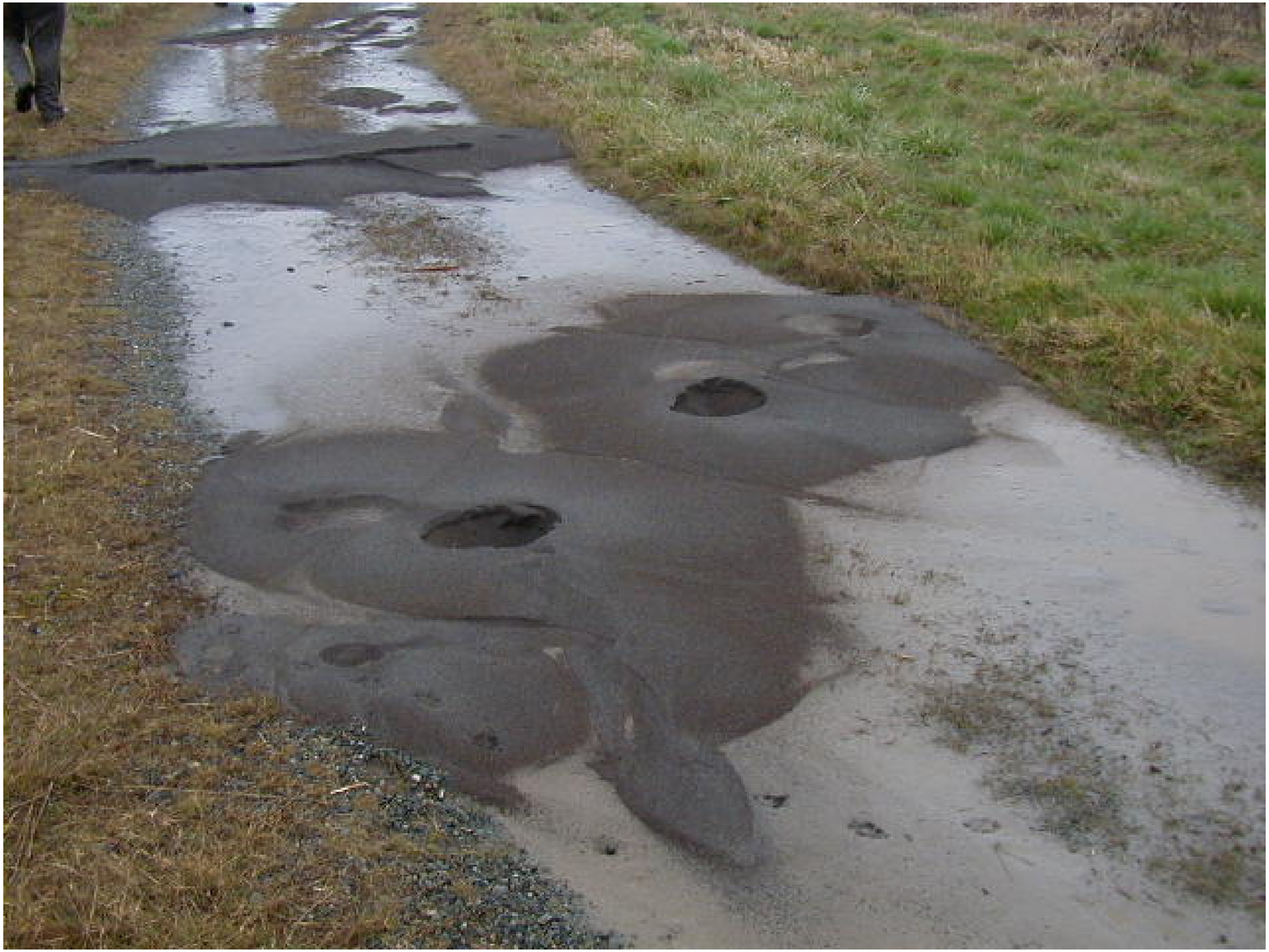
2/28/01
Mw = 6.8

PNSN Rapid Instrumental Intensity Map Epicenter: 17.6 km NE of Olympia, WA
Wed Feb 28, 2001 10:54:00 AM PST M 6.8 N47.15 W122.72 ID:0102281654

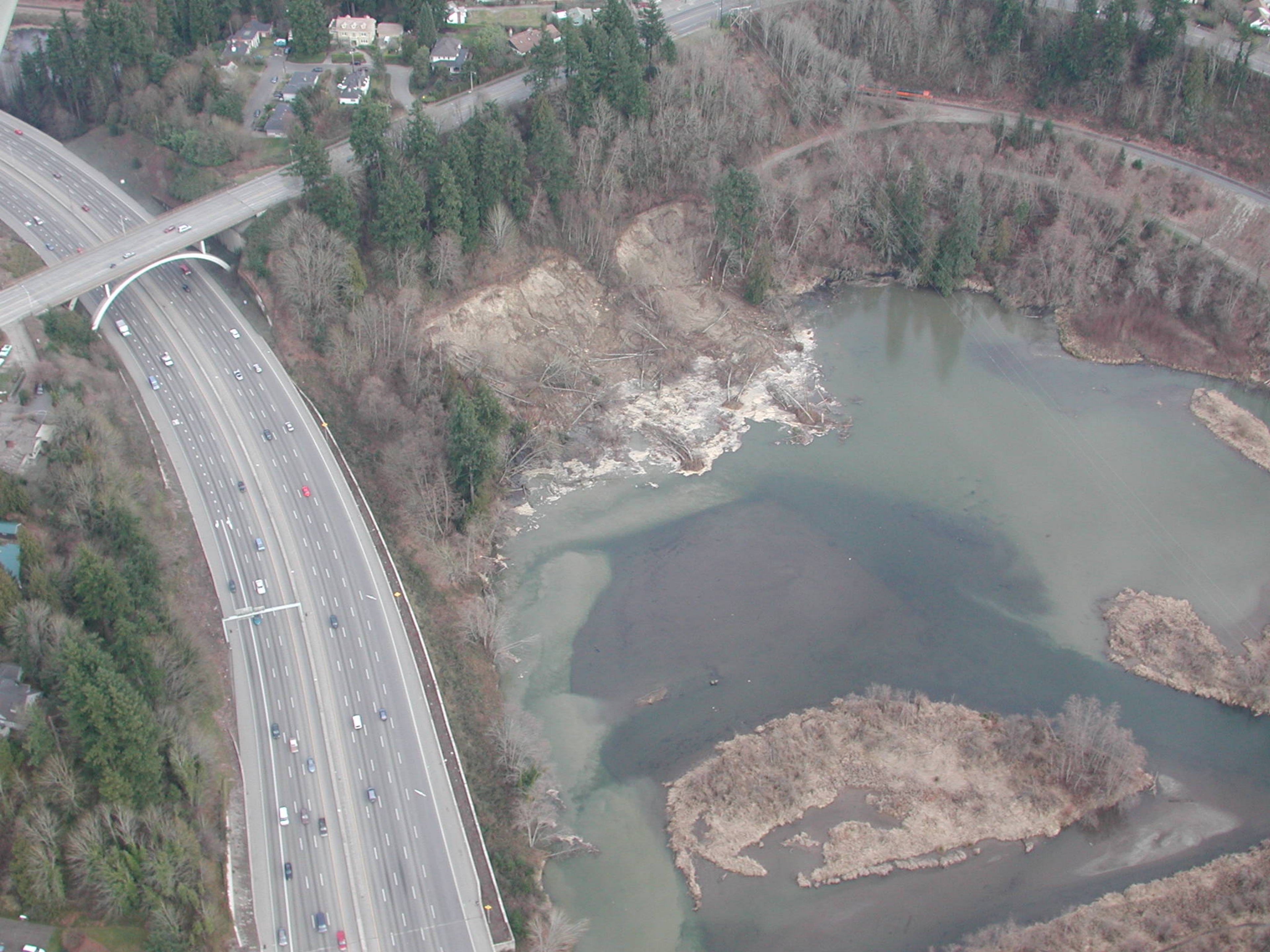


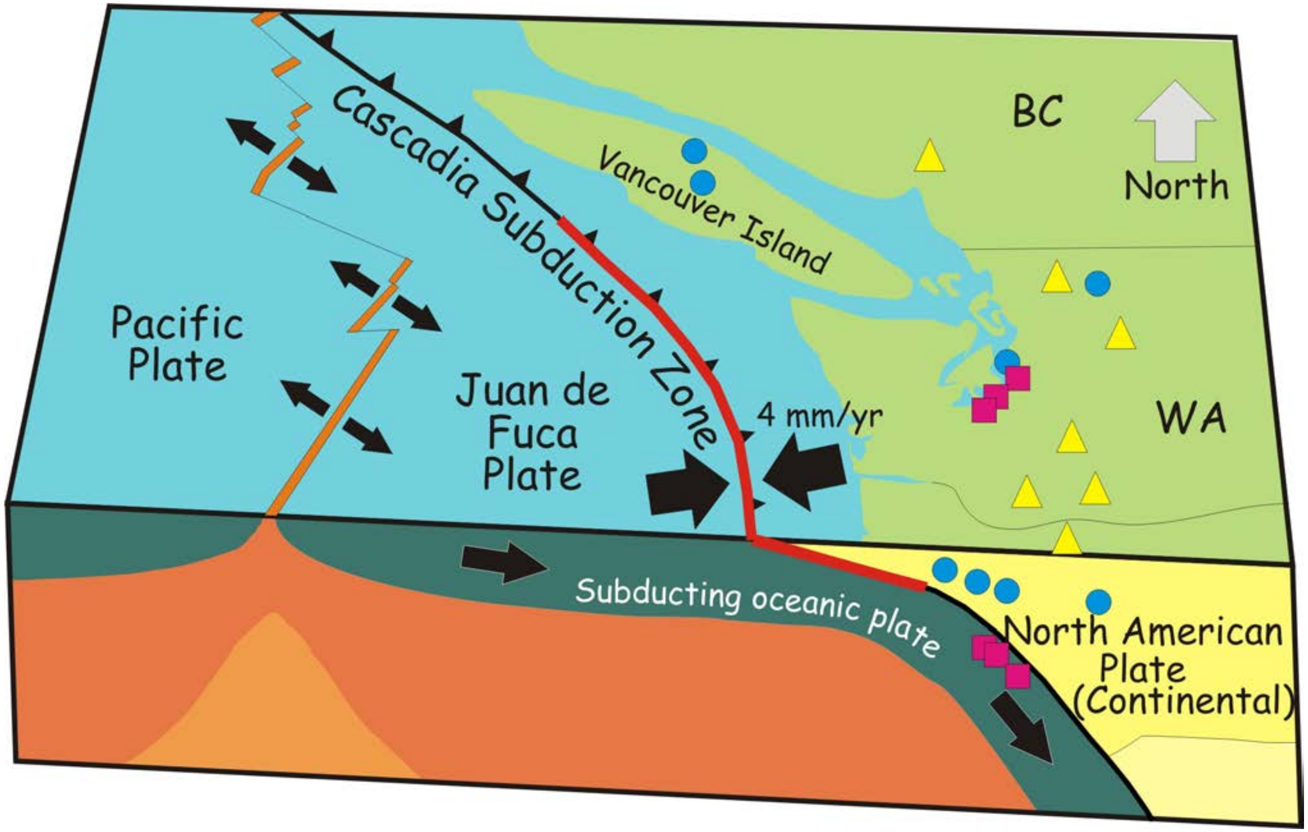
PROCESSED: Thu Apr 19, 2001 03:39:38 AM PDT.

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+



Movie





Earthquake Sources

■ Deep earthquakes (Intraslab)

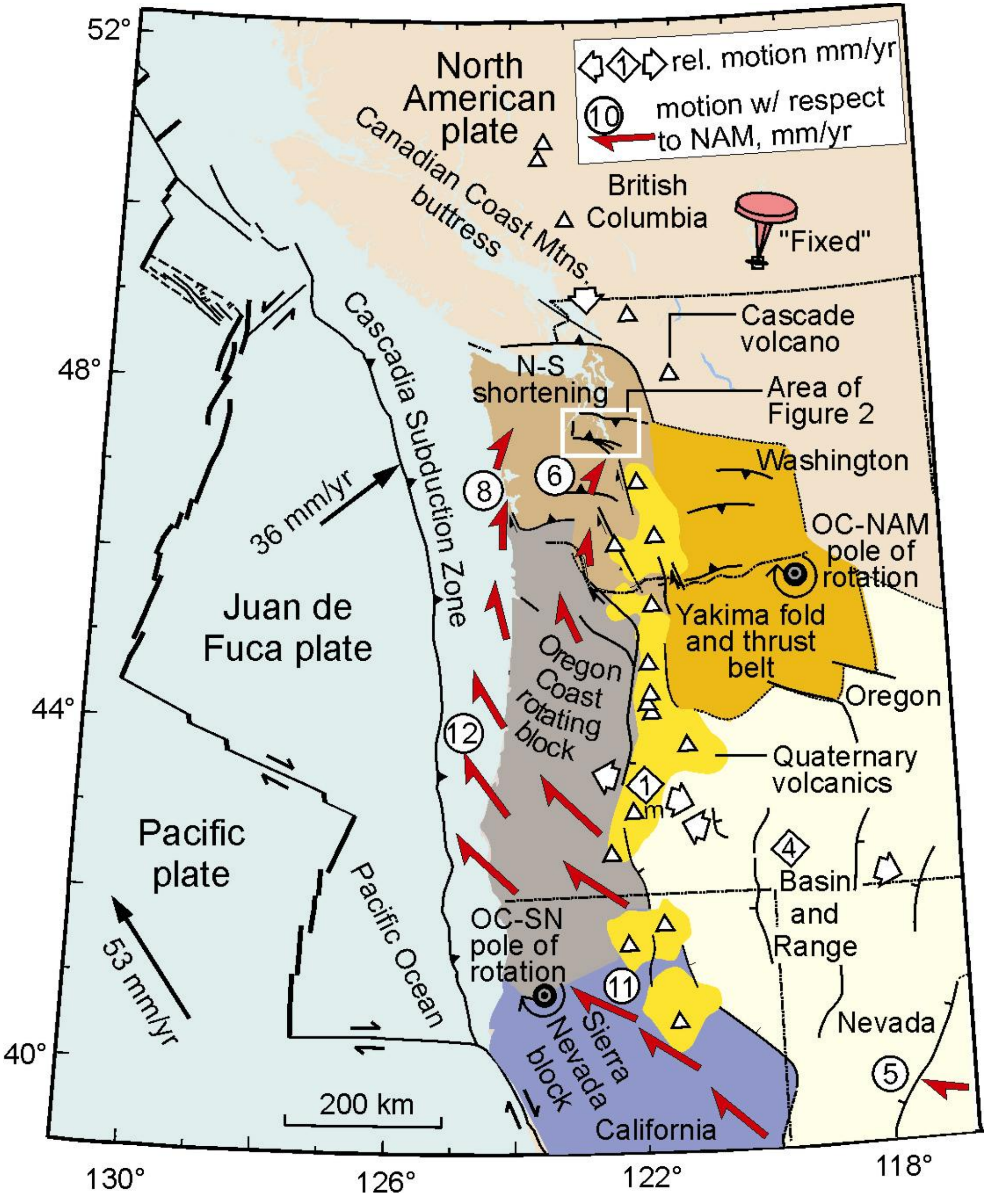
● Shallow earthquakes (in Nam)

╲ Subduction zone earthquakes

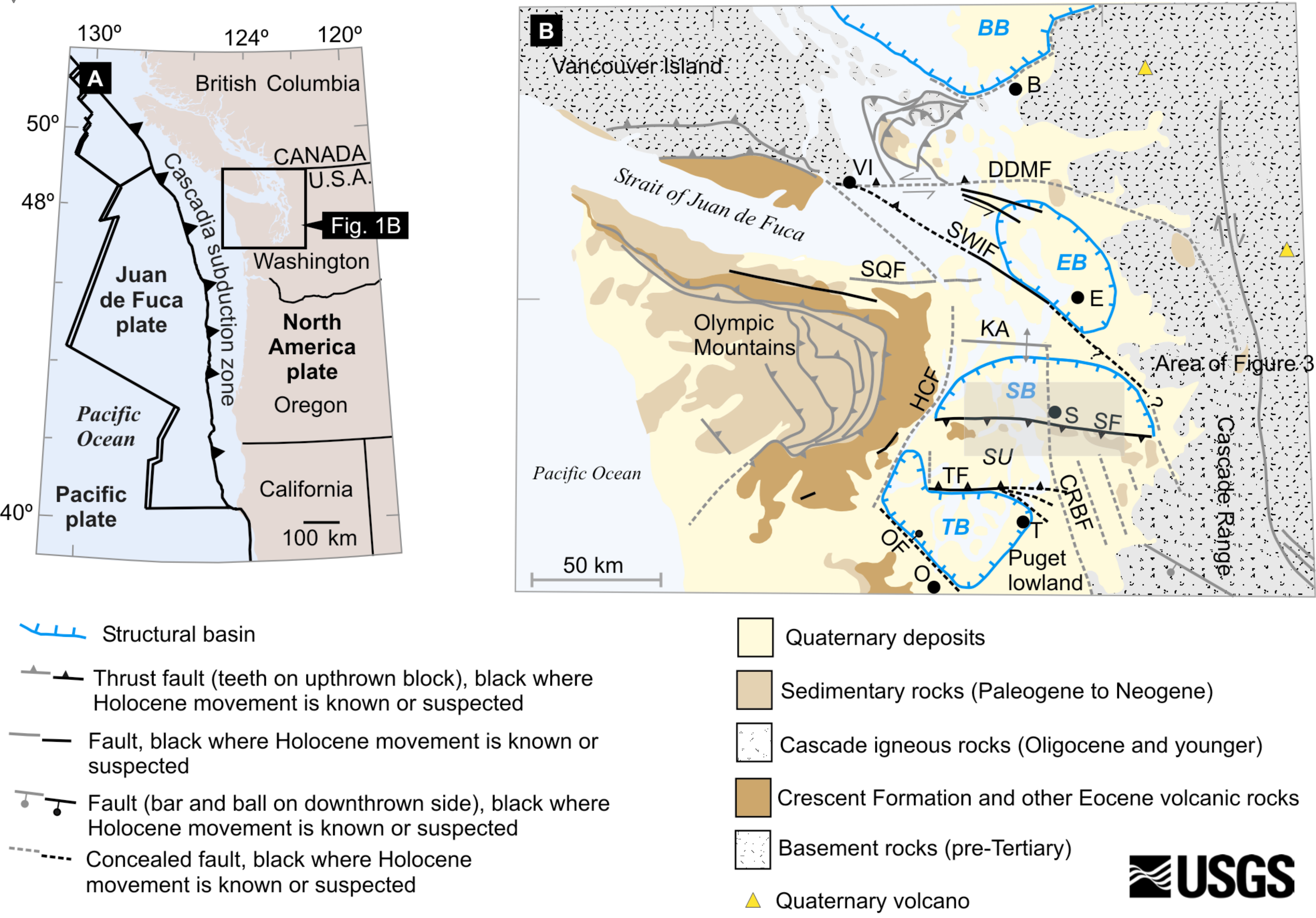
▲ Cascade volcano

N-S contraction inferred after removing effects of oblique E-W contraction from the subduction zone

D-DMFZ is the inferred edge of “backstop”.



USGS


A
130°
124°
120°
50°
48°
40°
British Columbia
CANADA
U.S.A.
Fig. 1B
Washington
Cascadia subduction zone
Juan de Fuca plate
North America plate
Oregon
Pacific Ocean
Pacific plate
California
100 km
B
Vancouver Island
BB
B
VI
DDMF
Strait of Juan de Fuca
SWIF
EB
E
SQF
KA
Olympic Mountains
HCF
Area of Figure 3
SB
S
SF
SU
TF
CRBF
TB
T
OF
O
Puget lowland
Cascade Range
Pacific Ocean
50 km
?
Structural basin
Thrust fault (teeth on upthrown block), black where Holocene movement is known or suspected
Fault, black where Holocene movement is known or suspected
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Crescent Formation and other Eocene volcanic rocks
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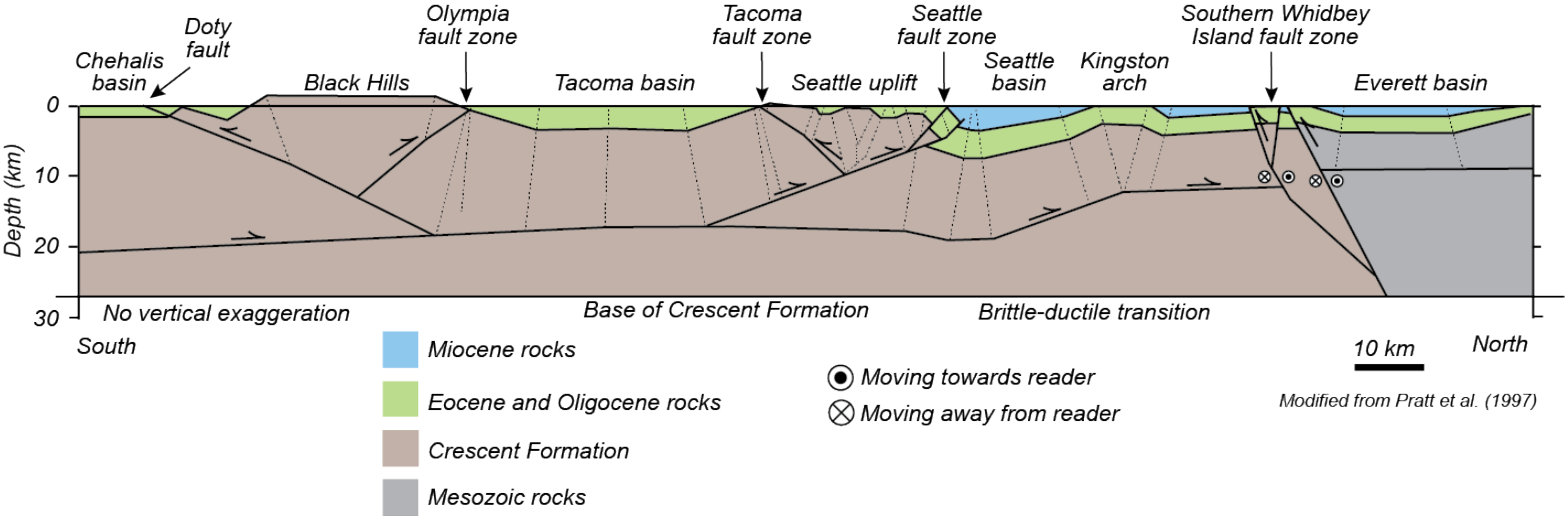
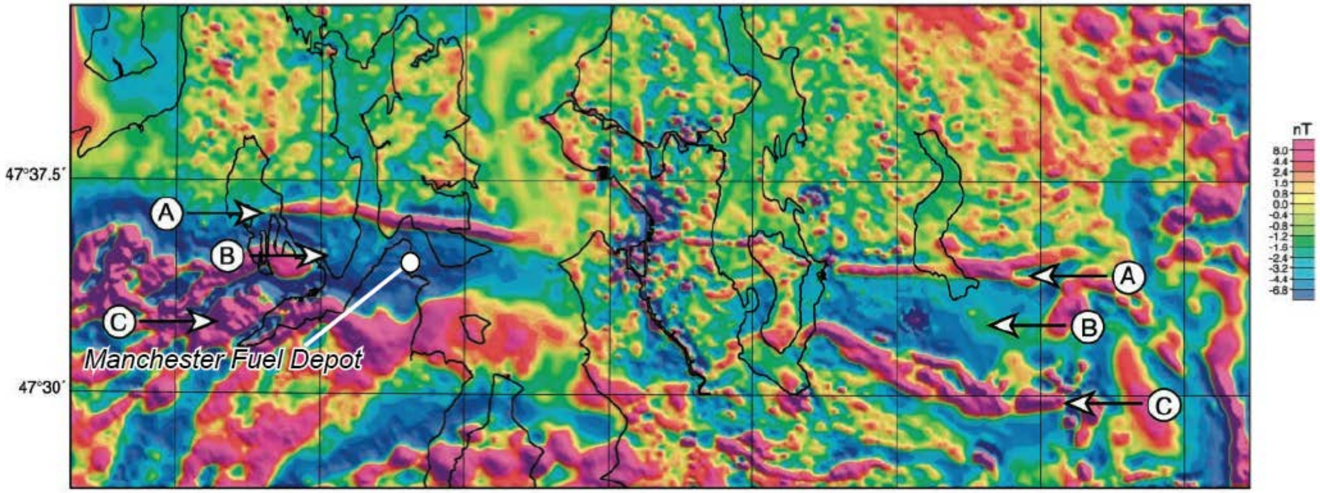


Modified from Pratt et al. (1997)



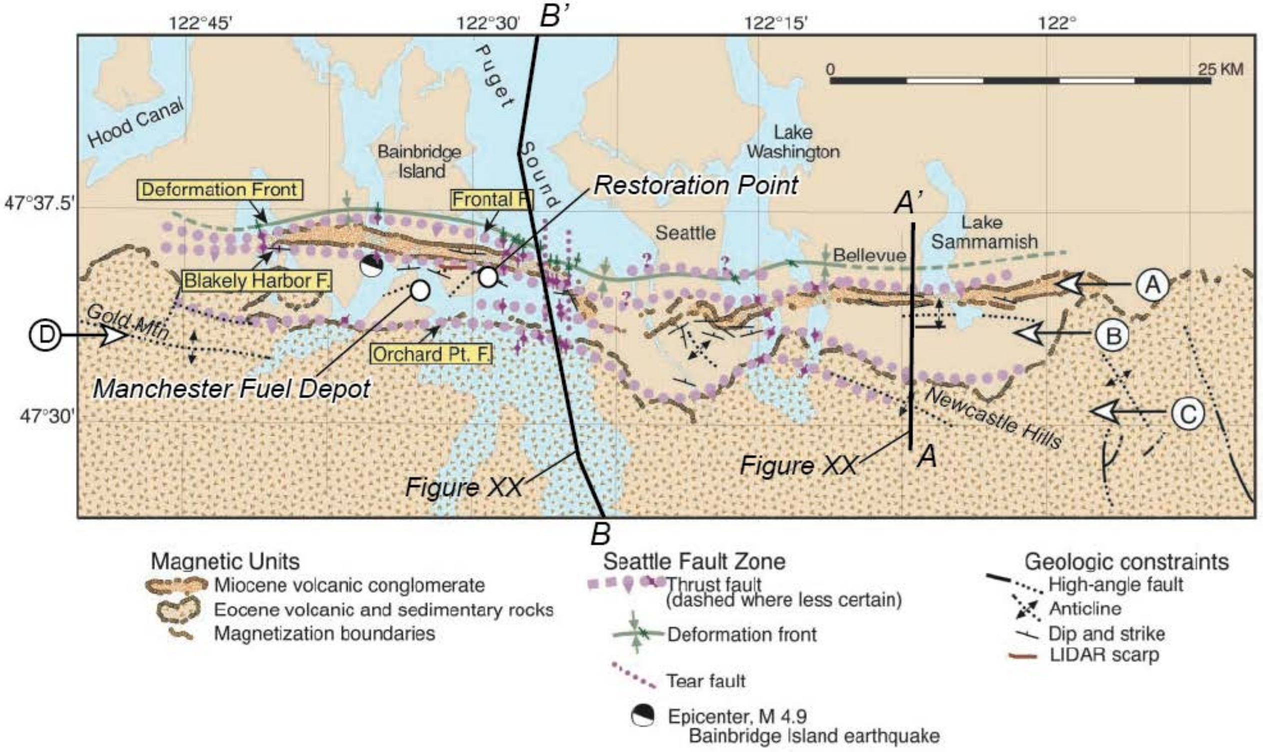
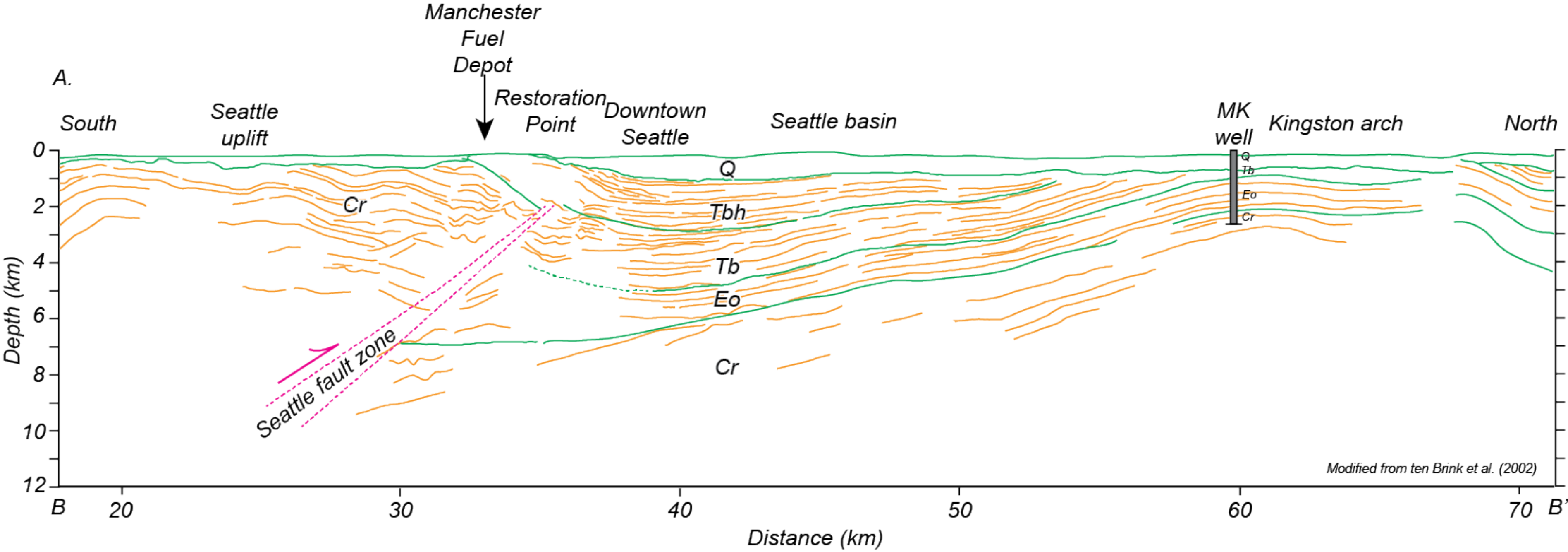
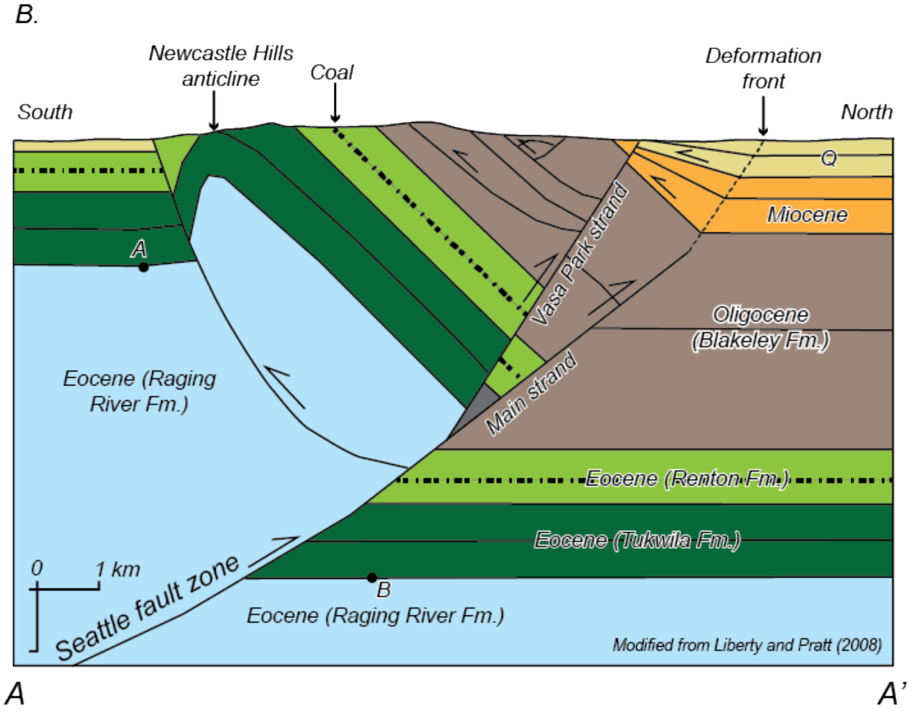


Image source: Blakely et al. (2002)

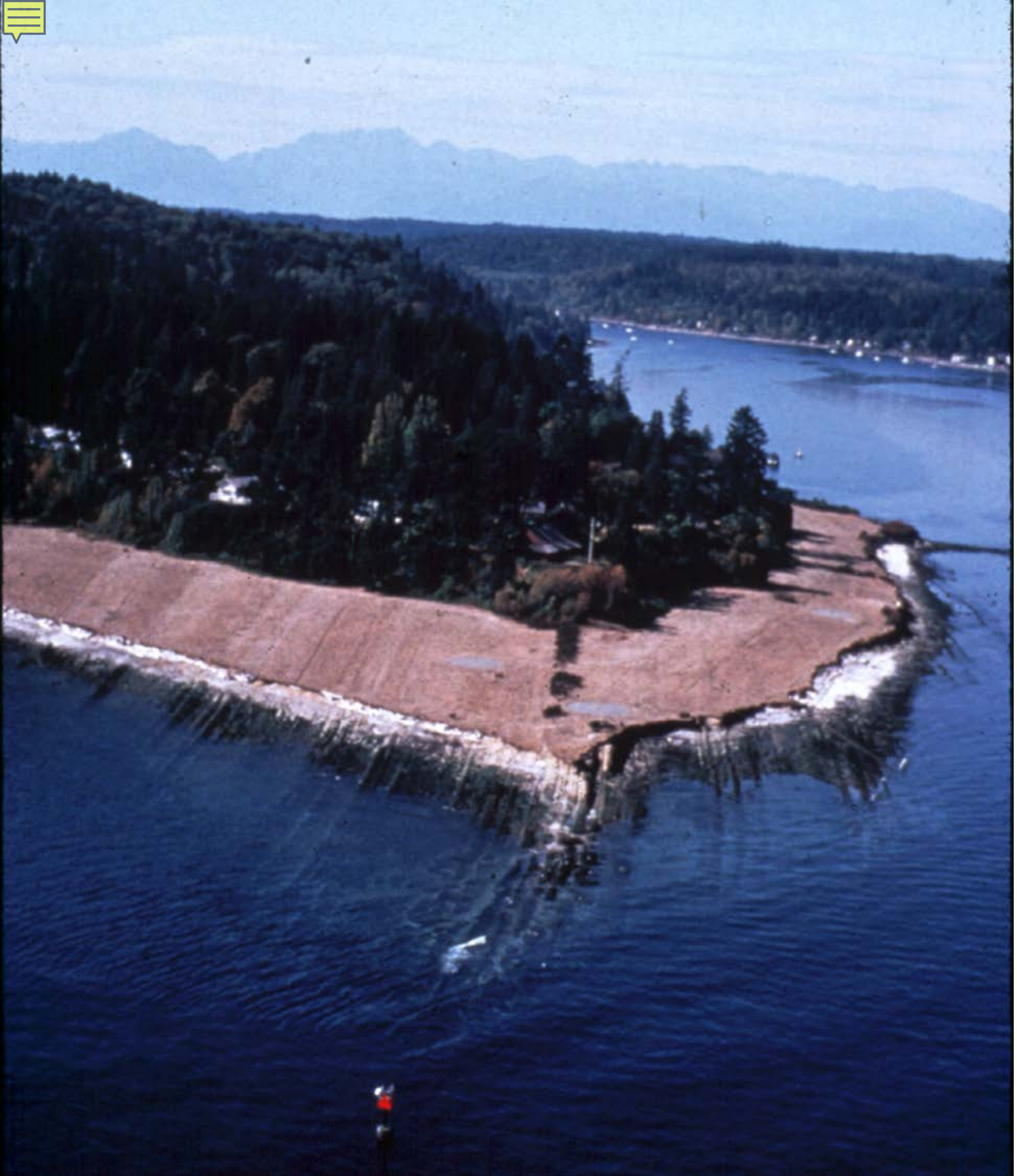


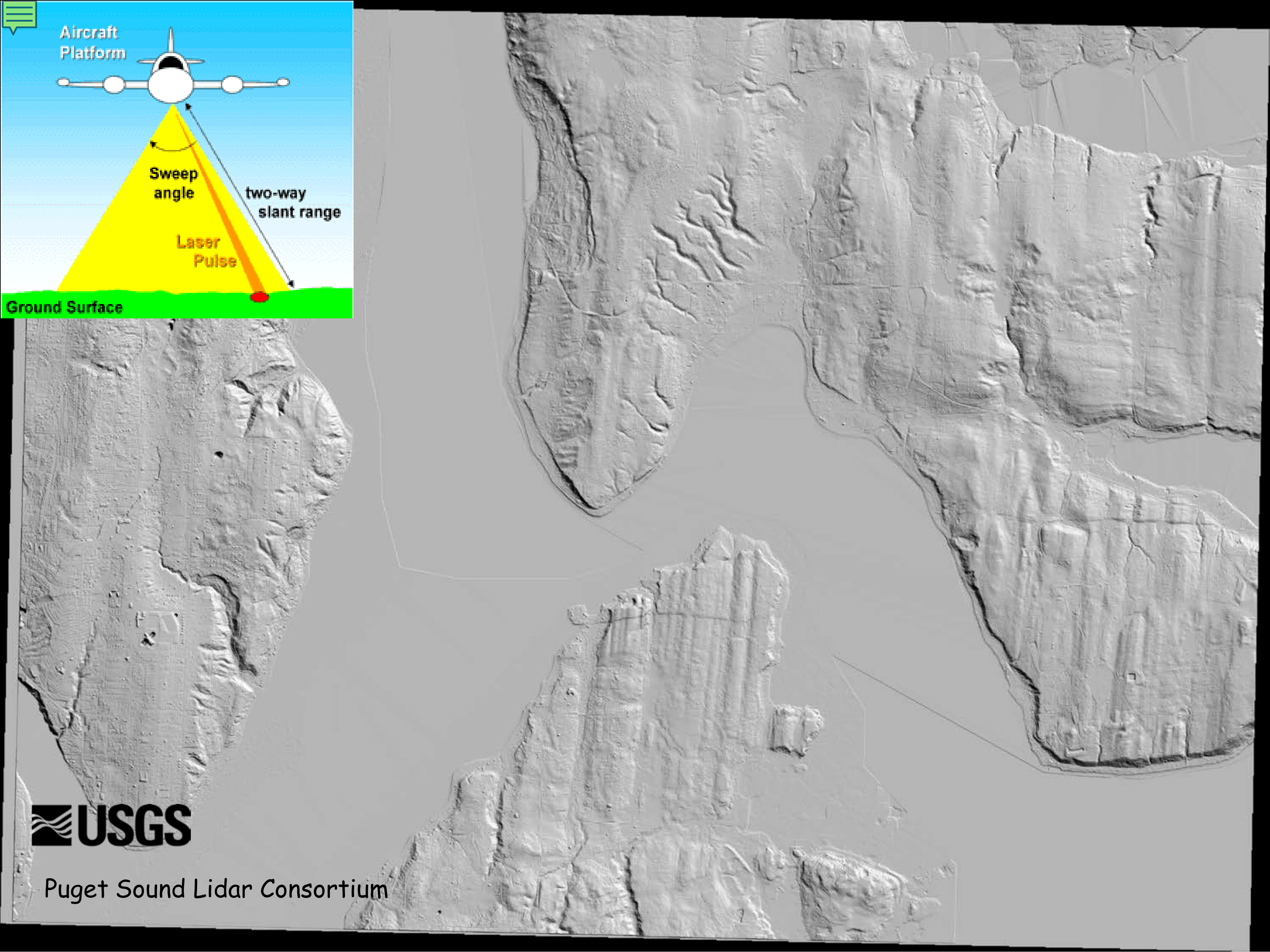
Modified from ten Brink et al. (2002)

No vertical exaggeration



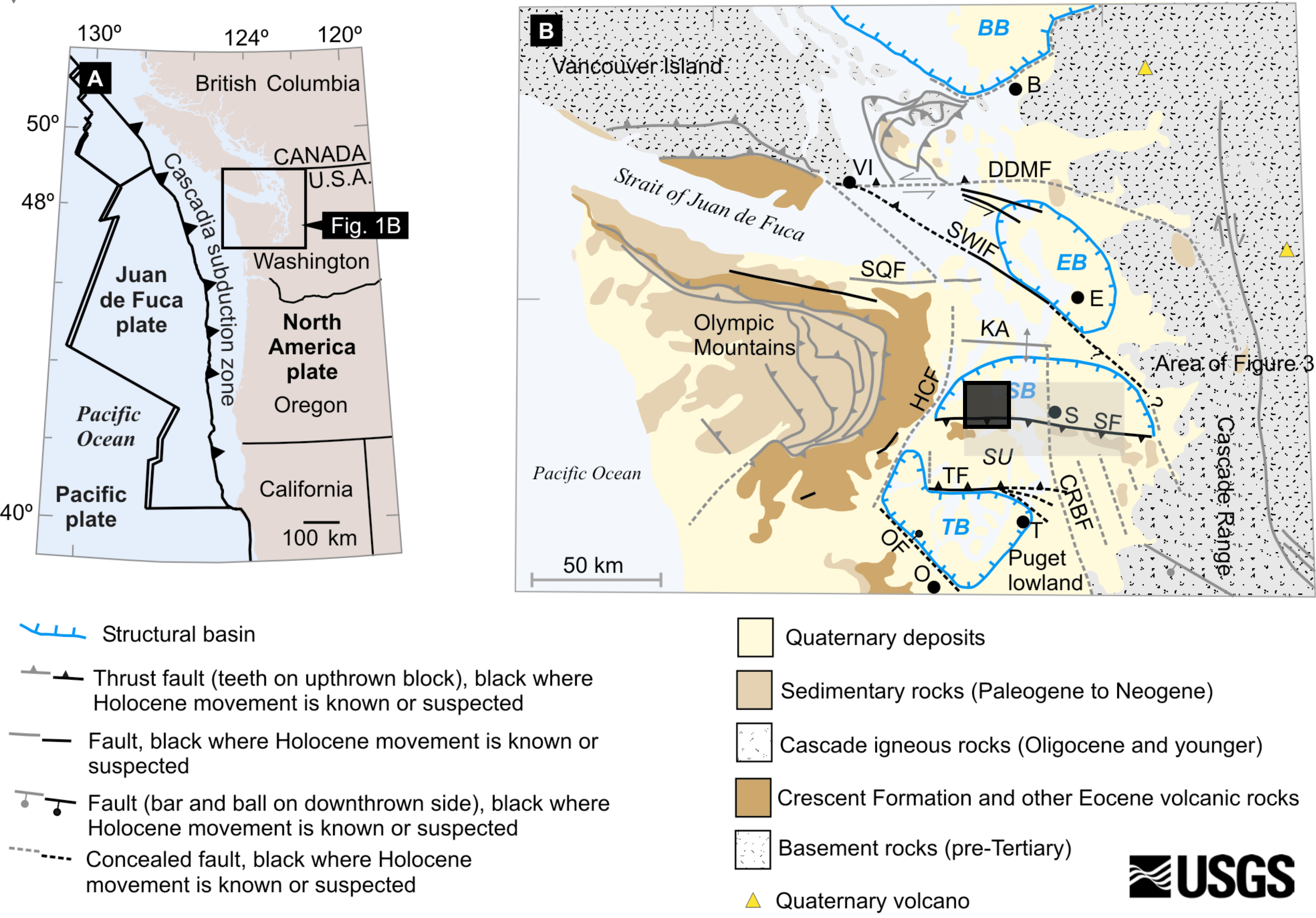
Modified from Liberty and Pratt (2008)





USGS

Puget Sound Lidar Consortium


A
130º
124º
120º
50º
48º
40º
British Columbia
CANADA
U.S.A.
Fig. 1B
Cascadia subduction zone
Washington
Juan de Fuca plate
North America plate
Oregon
Pacific Ocean
Pacific plate
California
100 km
B
Vancouver Island
BB
B
VI
DDMF
Strait of Juan de Fuca
SWIF
EB
E
SQF
Olympic Mountains
KA
Area of Figure 3
HCF
SB
S
SF
SU
TF
CRBF
TB
T
OF
O
Puget lowland
Cascade Range
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50 km
Structural basin
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Fault, black where Holocene movement is known or suspected
Fault (bar and ball on downthrown side), black where Holocene movement is known or suspected
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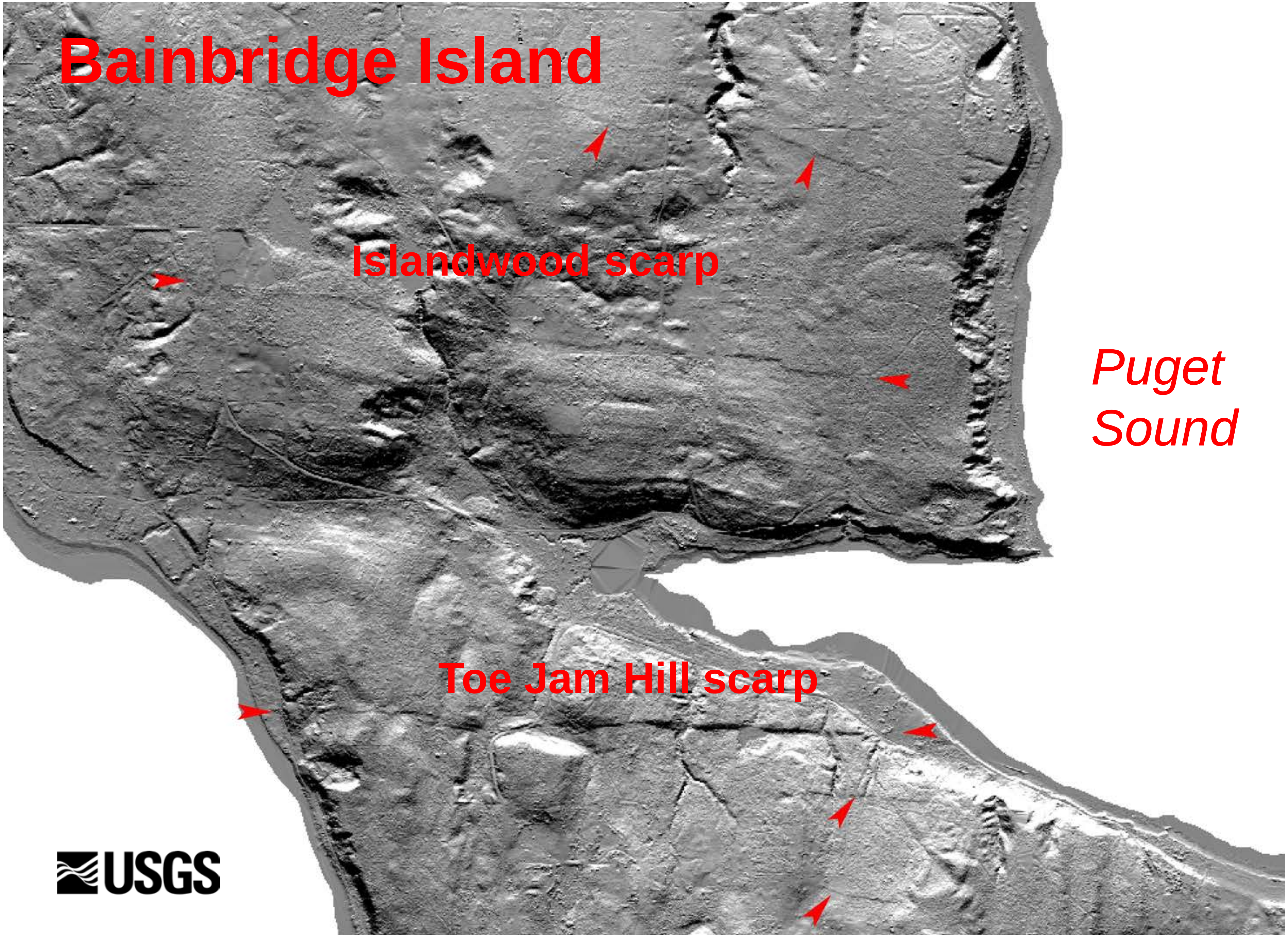
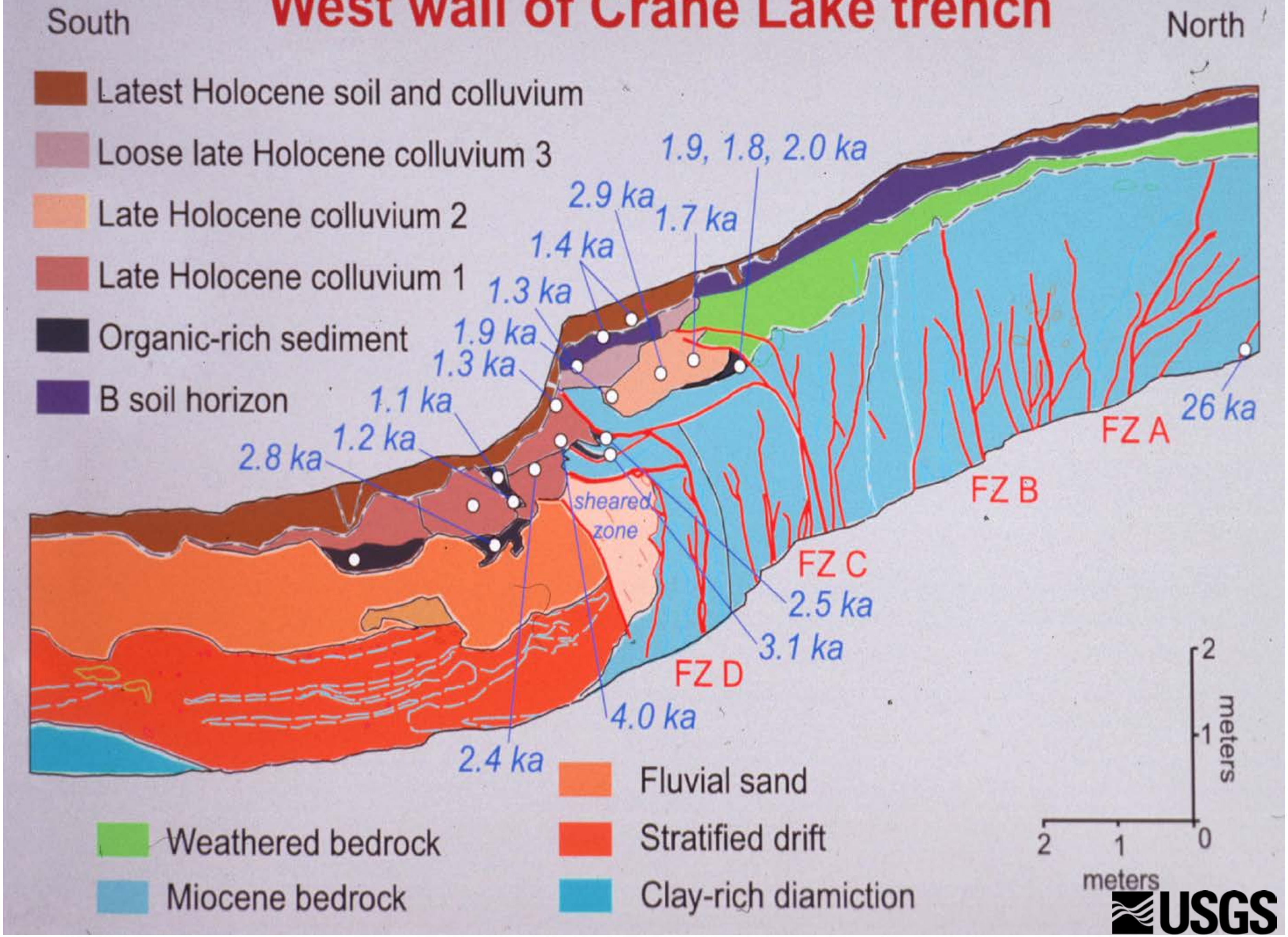
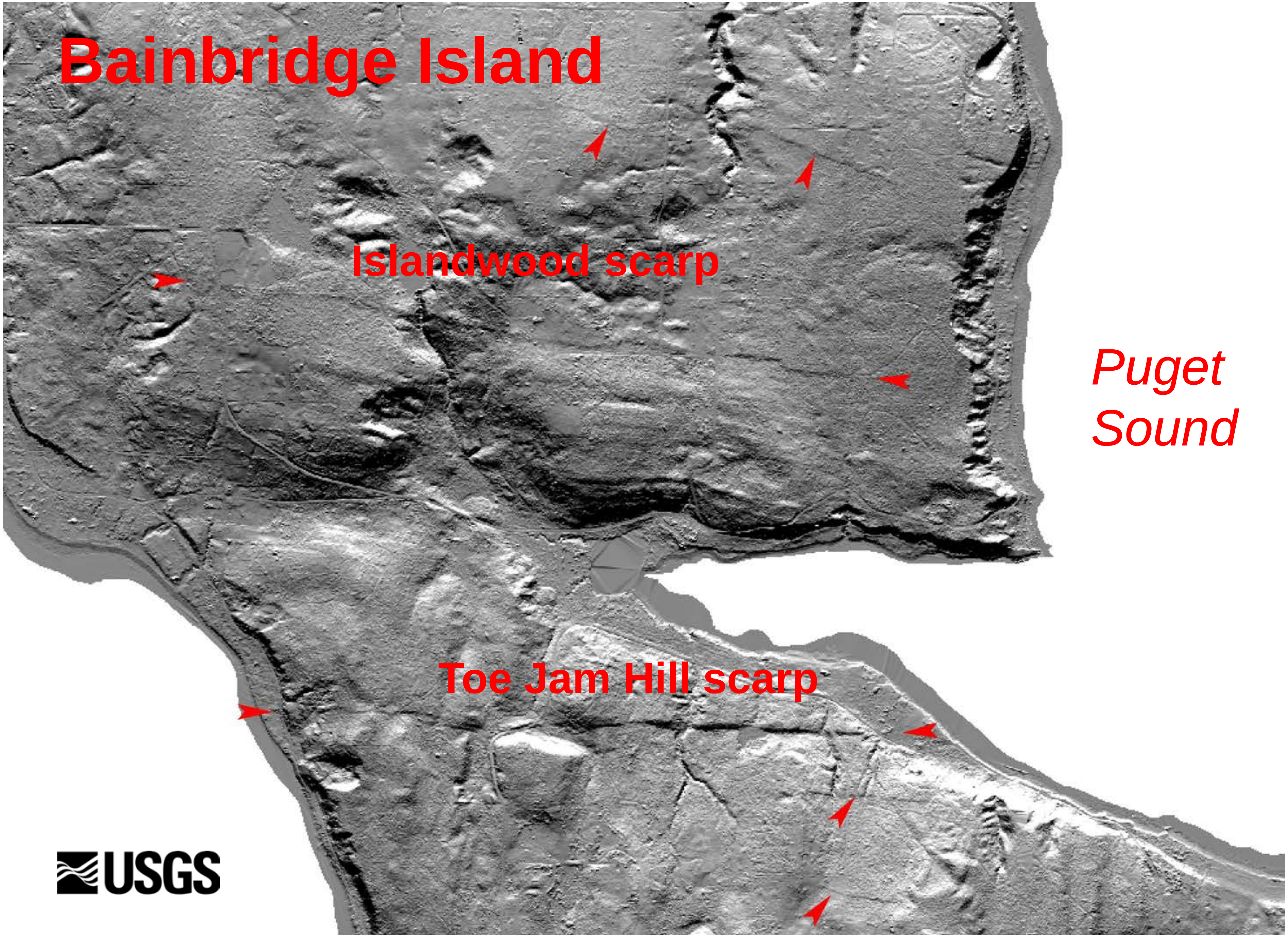
Basement rocks (pre-Tertiary)
Quaternary volcano

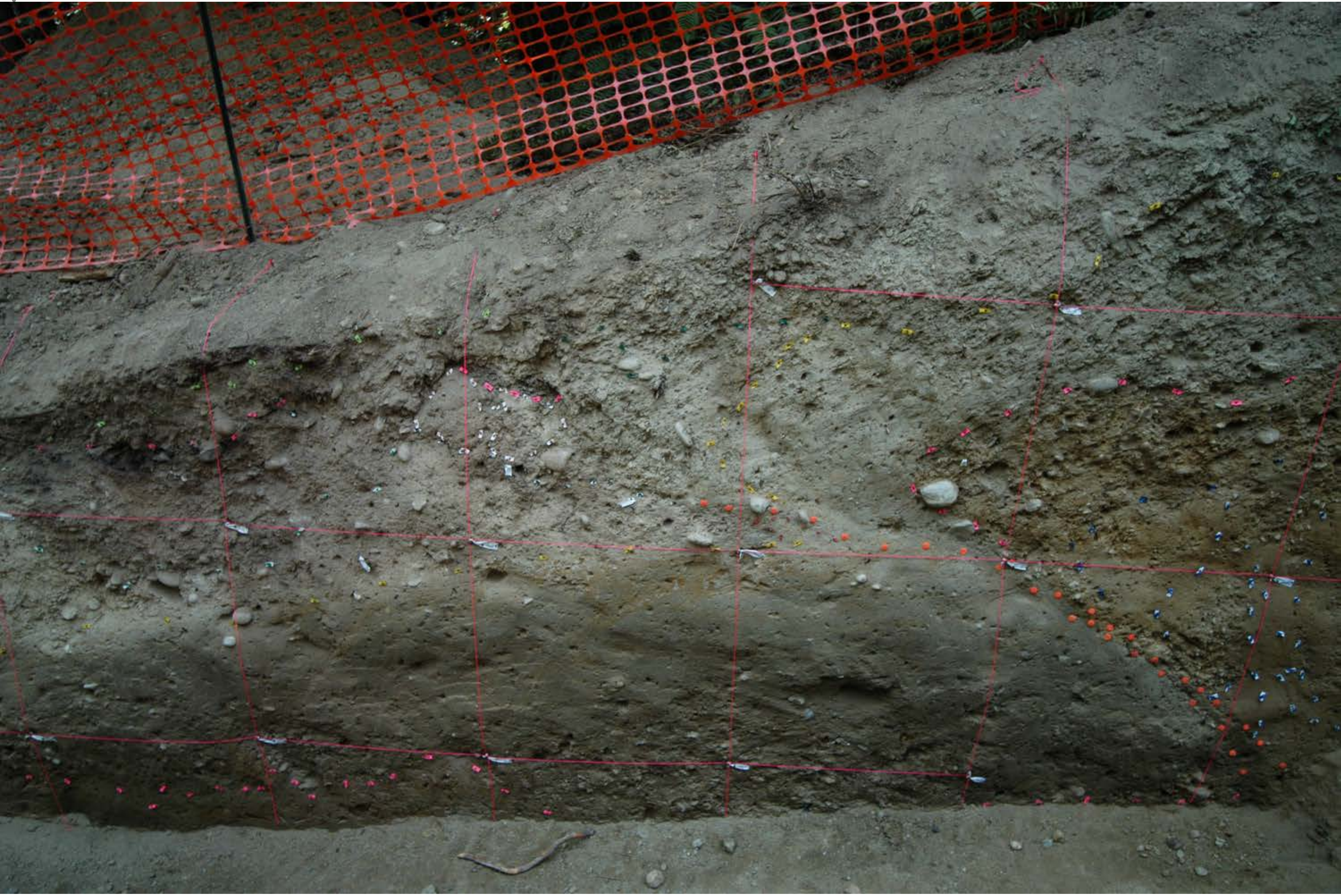

Bainbridge Island
Islandwood scarp
Toe Jam Hill scarp
Puget Sound
USGS

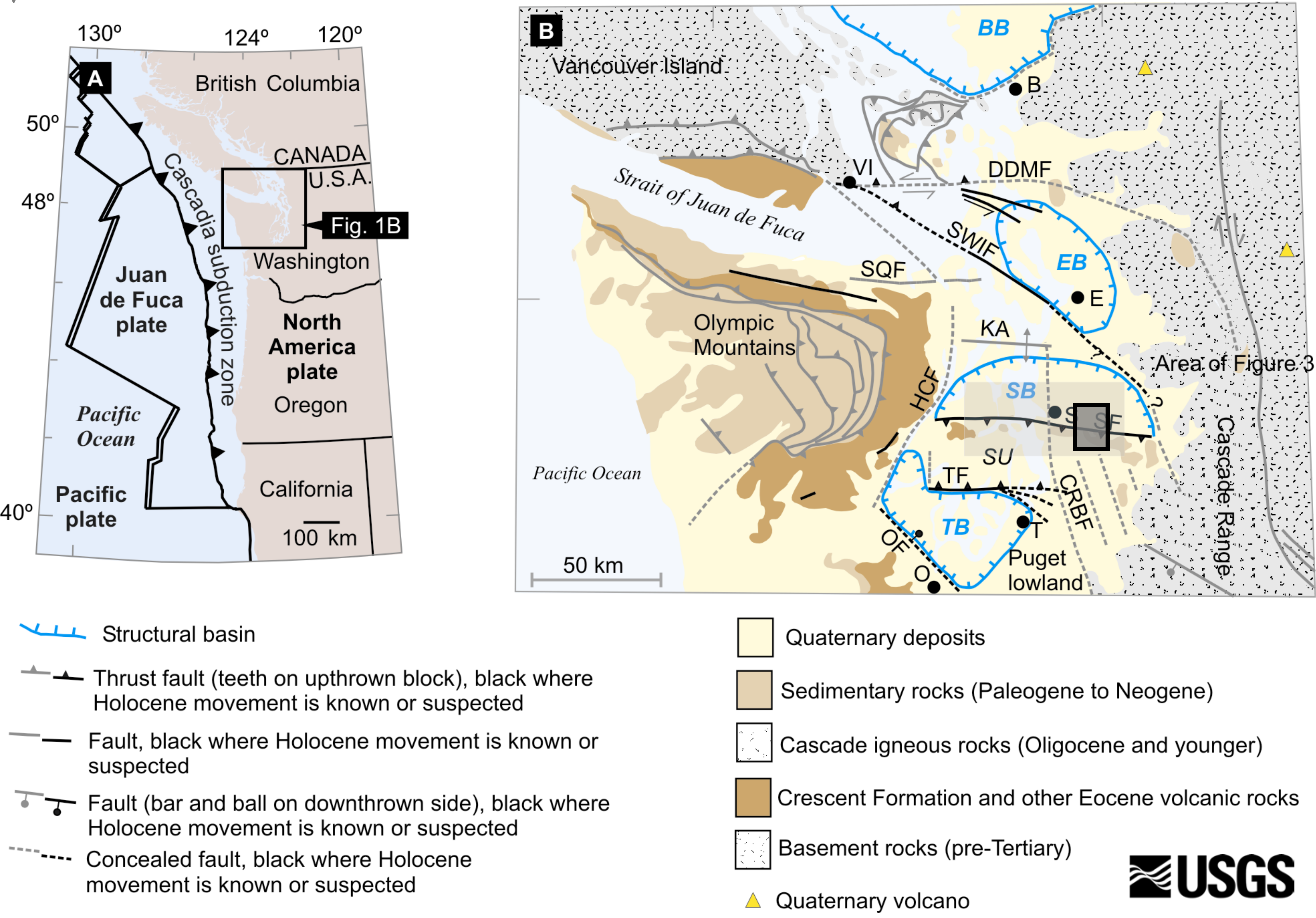
USGS

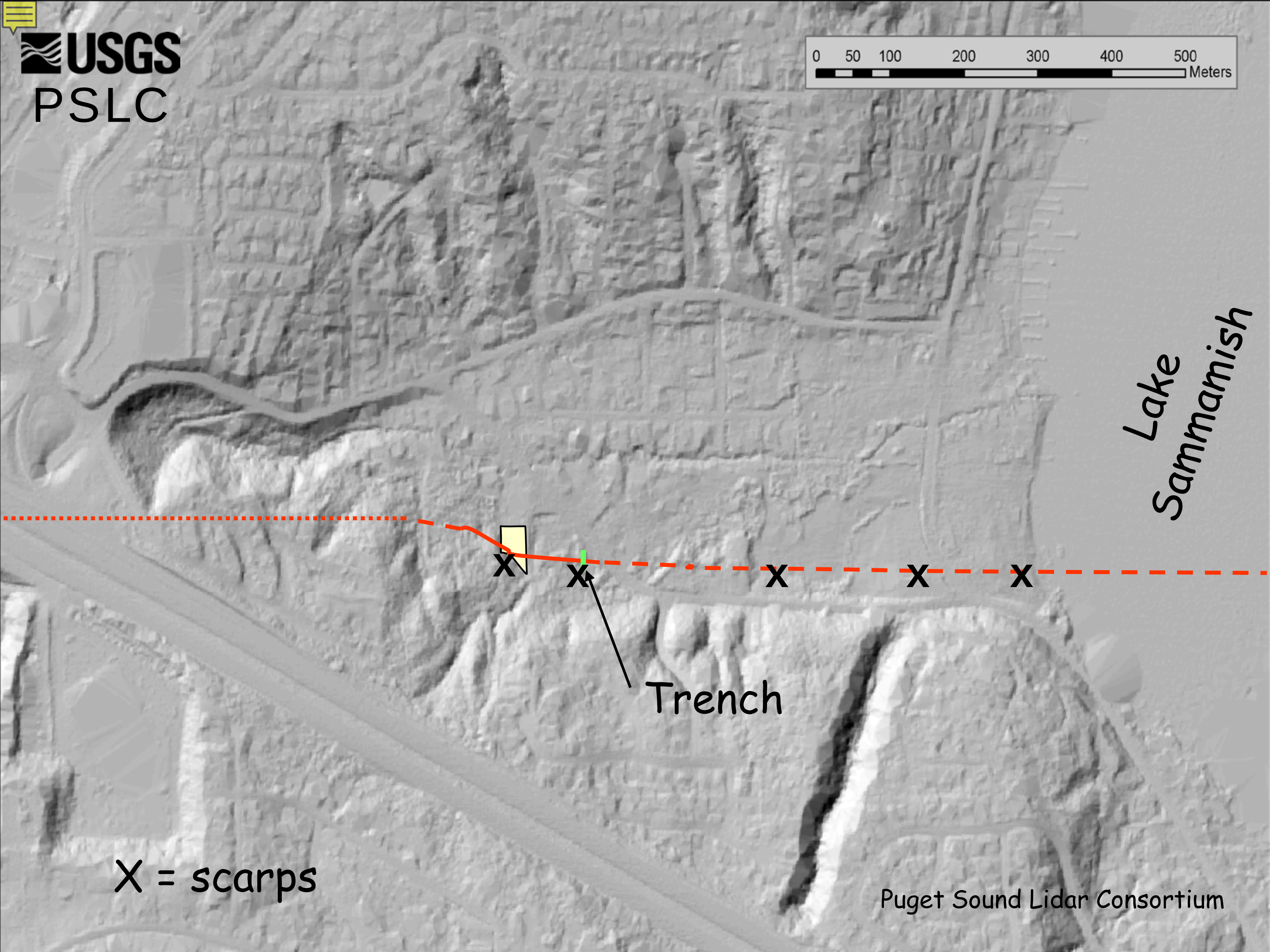
West wall of Crane Lake trench

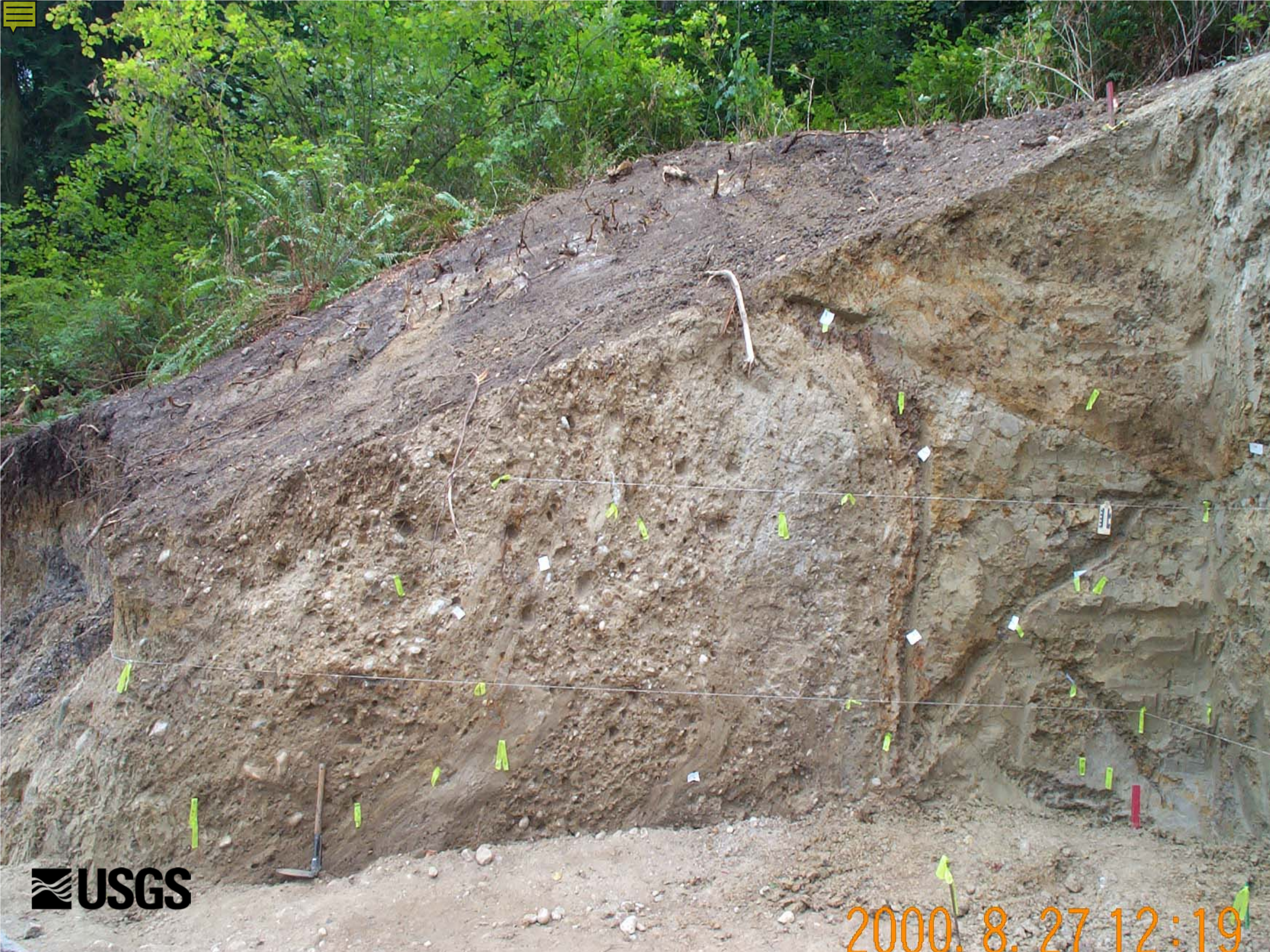


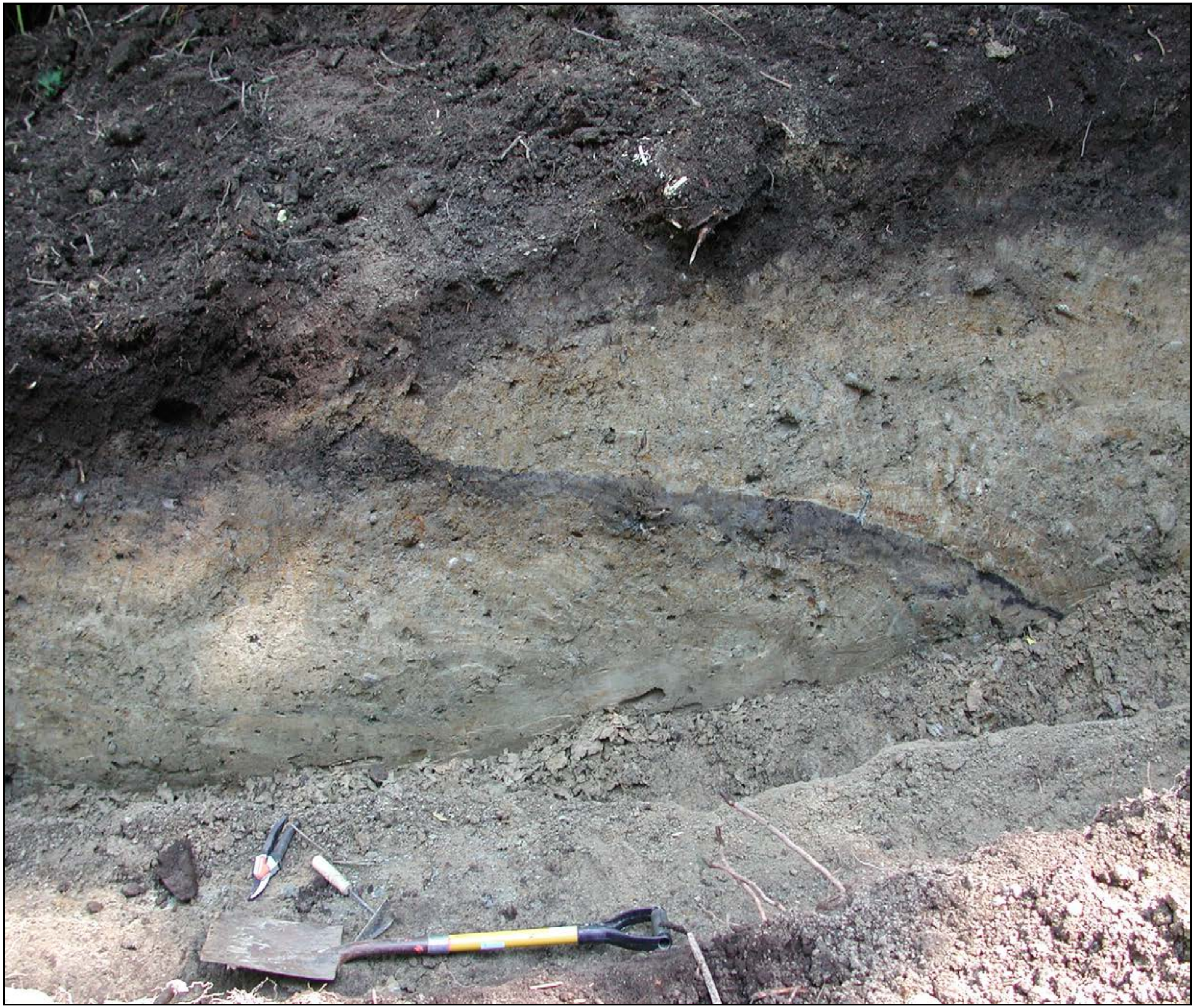

Bainbridge Island
Islandwood scarp
Puget Sound
Toe Jam Hill scarp



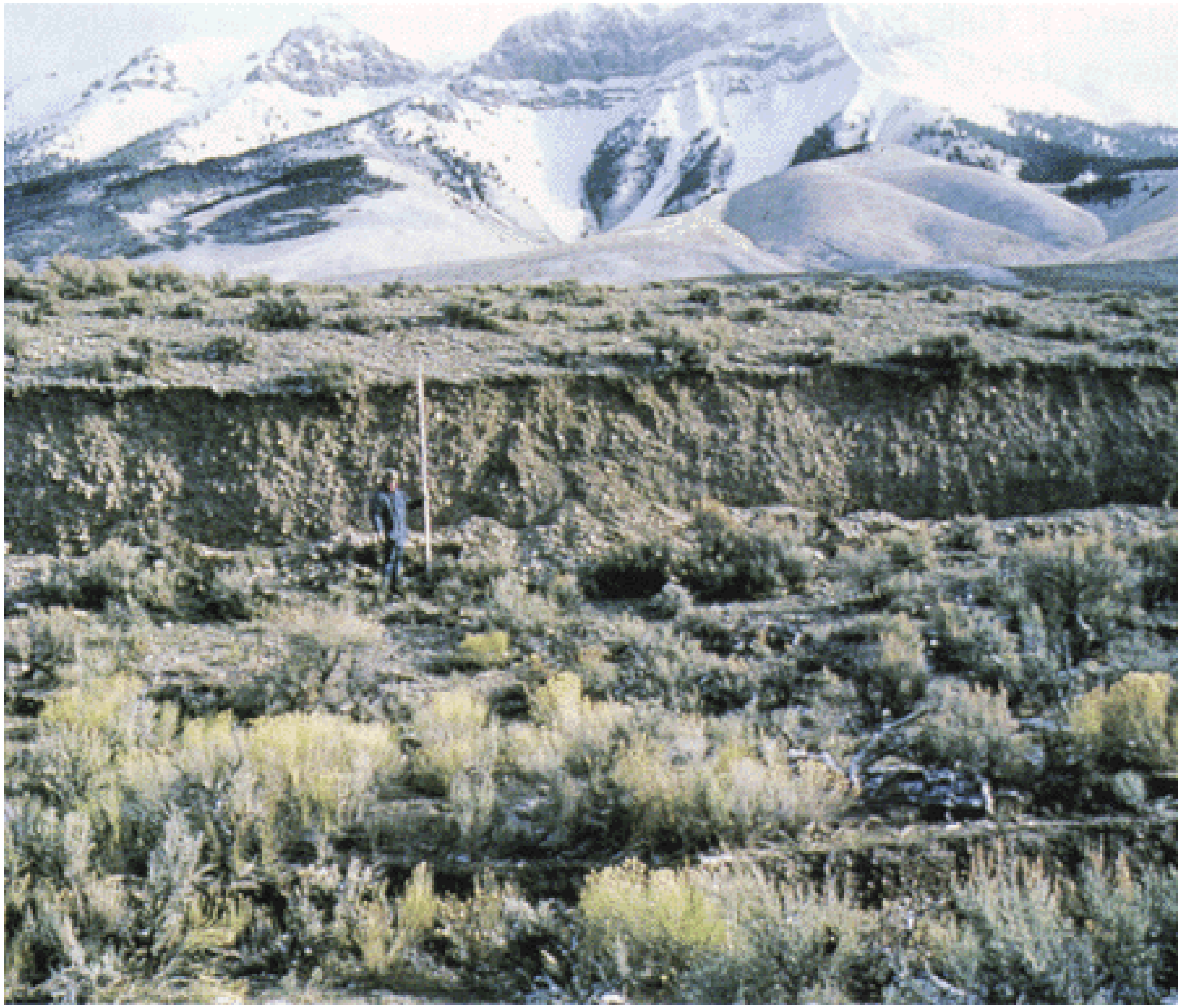

A
130°
124°
120°
50°
48°
40°
British Columbia
CANADA
U.S.A.
Fig. 1B
Washington
Cascadia subduction zone
Juan de Fuca plate
North America plate
Oregon
Pacific Ocean
Pacific plate
California
100 km
B
Vancouver Island
BB
B
VI
DDMF
Strait of Juan de Fuca
SWIF
EB
E
SQF
KA
Olympic Mountains
Area of Figure 3
HCF
SB
S
SF
SU
?
TF
CRBF
TB
T
OF
O
Puget lowland
Cascade Range
Pacific Ocean
50 km
Structural basin
Thrust fault (teeth on upthrown block), black where Holocene movement is known or suspected
Fault, black where Holocene movement is known or suspected
Fault (bar and ball on downthrown side), black where Holocene movement is known or suspected
Concealed fault, black where Holocene movement is known or suspected
Quaternary deposits
Sedimentary rocks (Paleogene to Neogene)
Cascade igneous rocks (Oligocene and younger)
Crescent Formation and other Eocene volcanic rocks
Basement rocks (pre-Tertiary)
Quaternary volcano

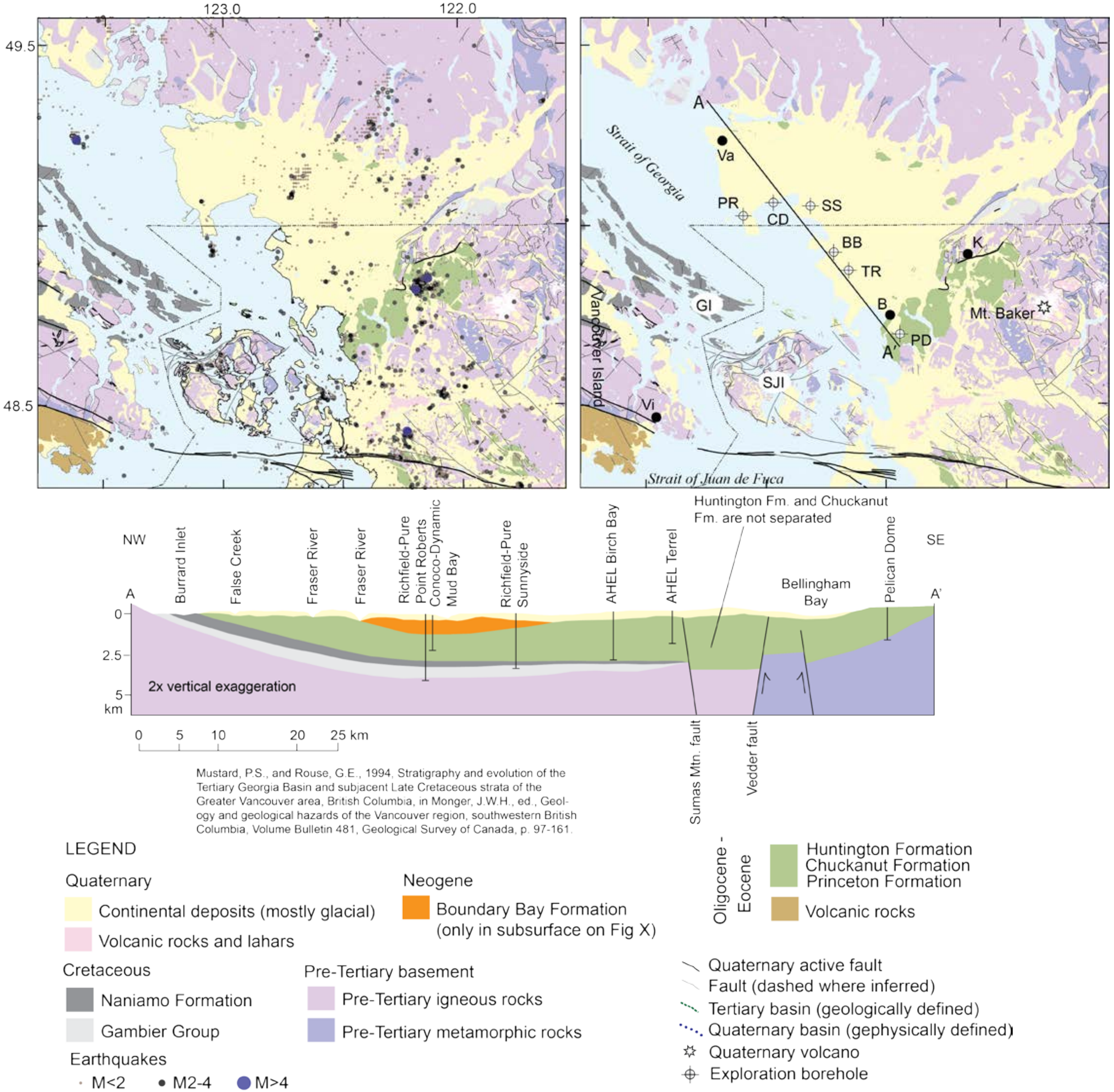

USGS
PSLC
0 50 100 200 300 400 500 Meters
Lake Sammamish
X
X
X
X
X
Trench
X = scarps
Puget Sound Lidar Consortium


USGS
2000. 8. 27 12:19

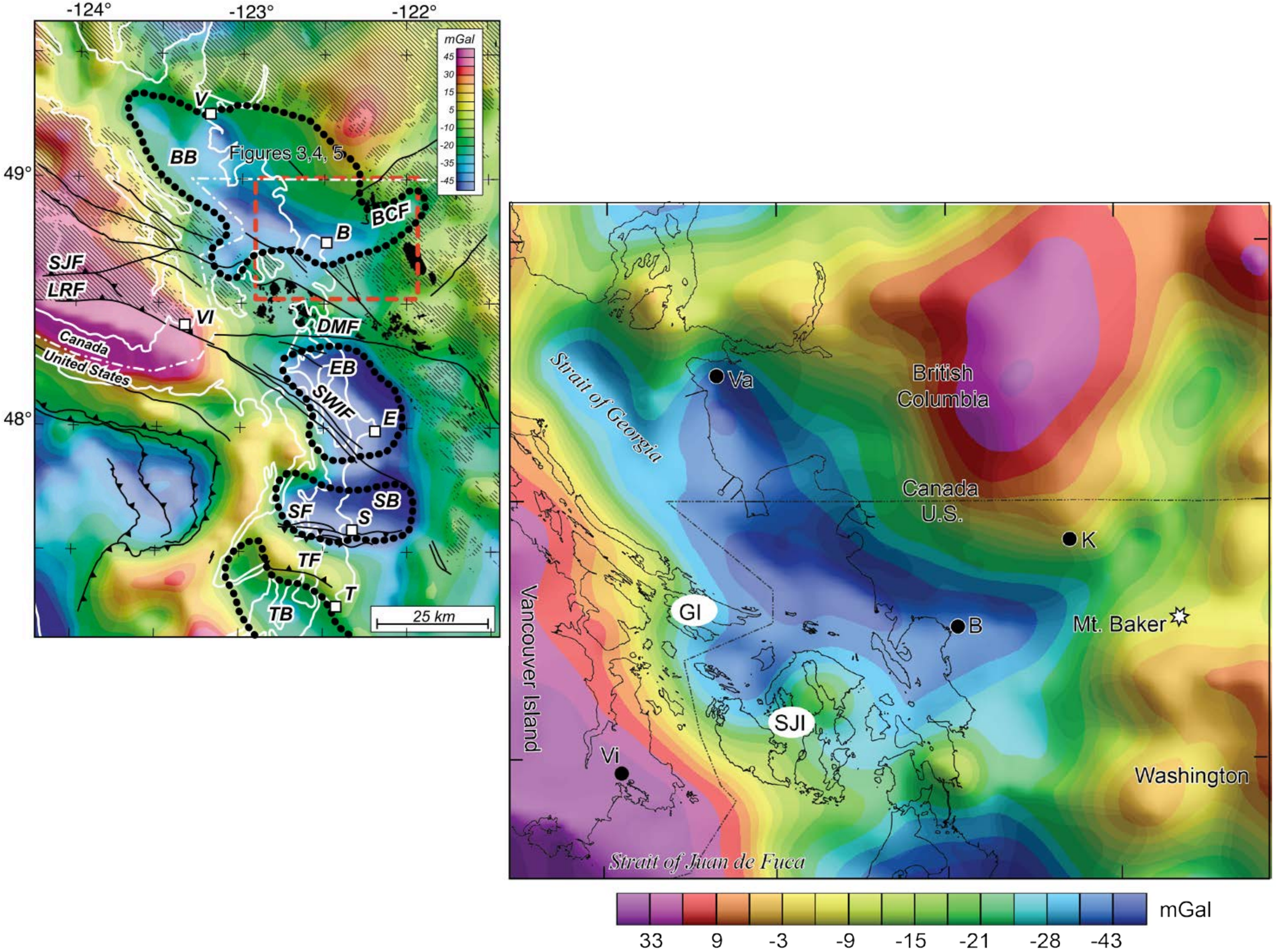


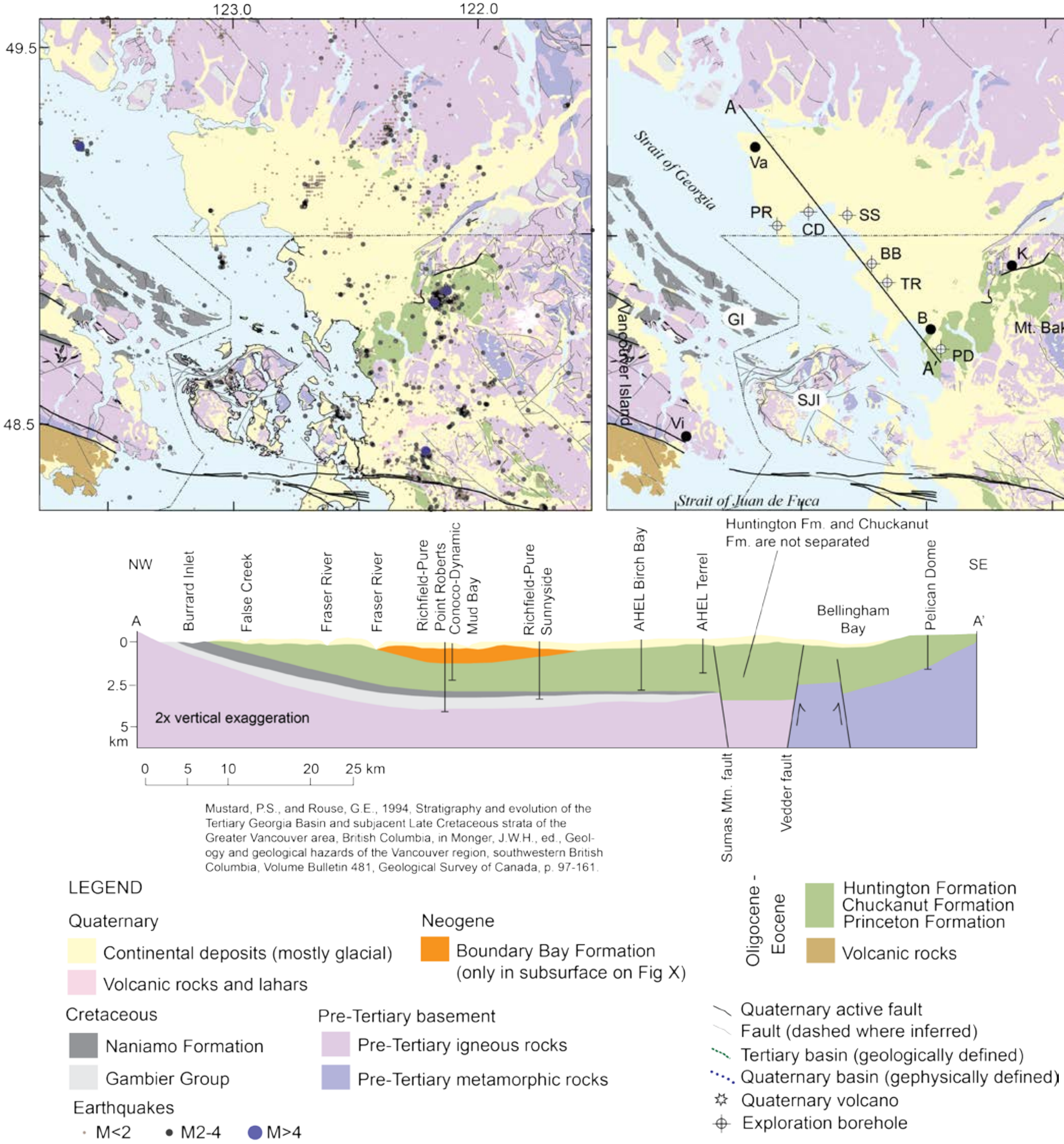
Borah Peak, Idaho – 1983 M7.3



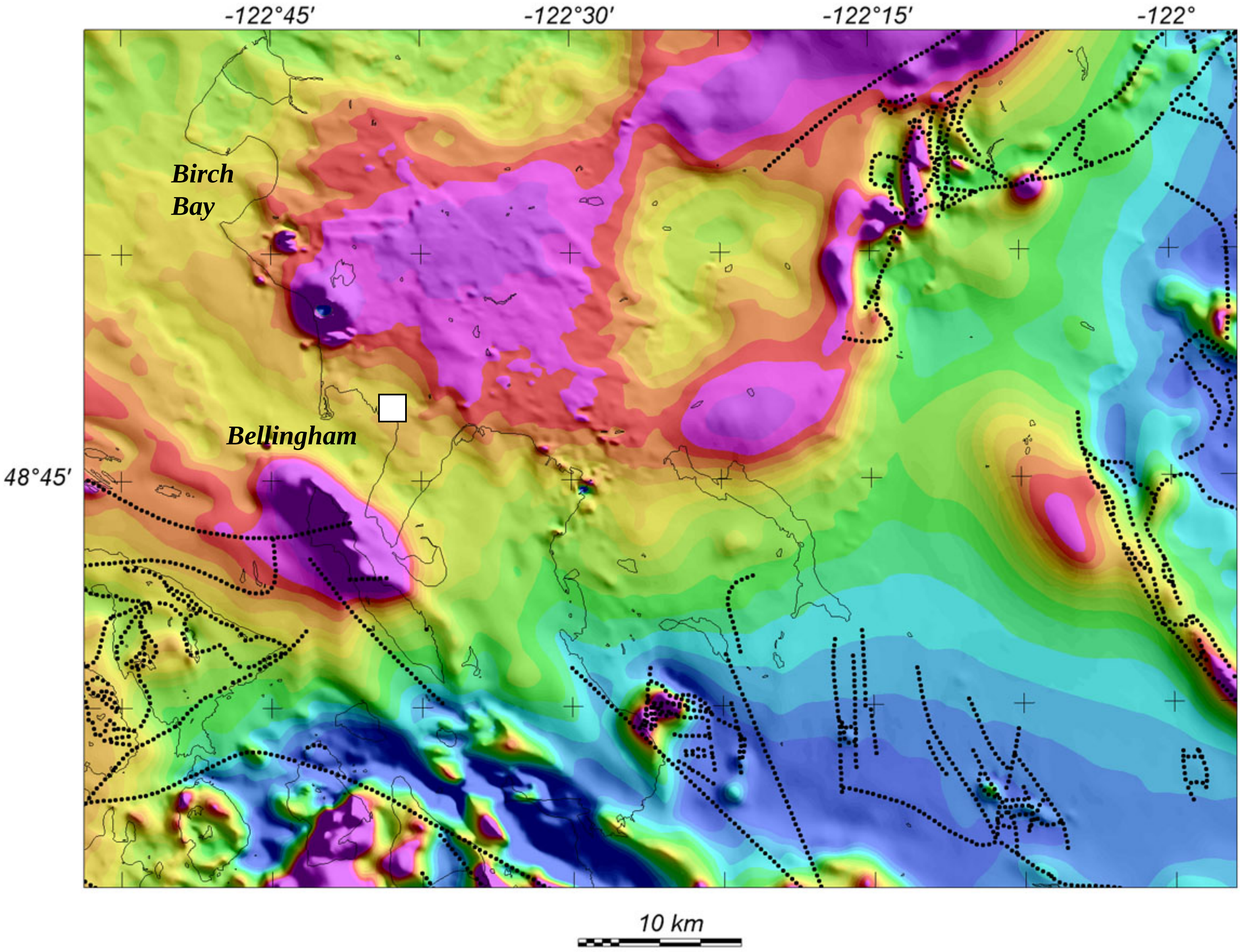


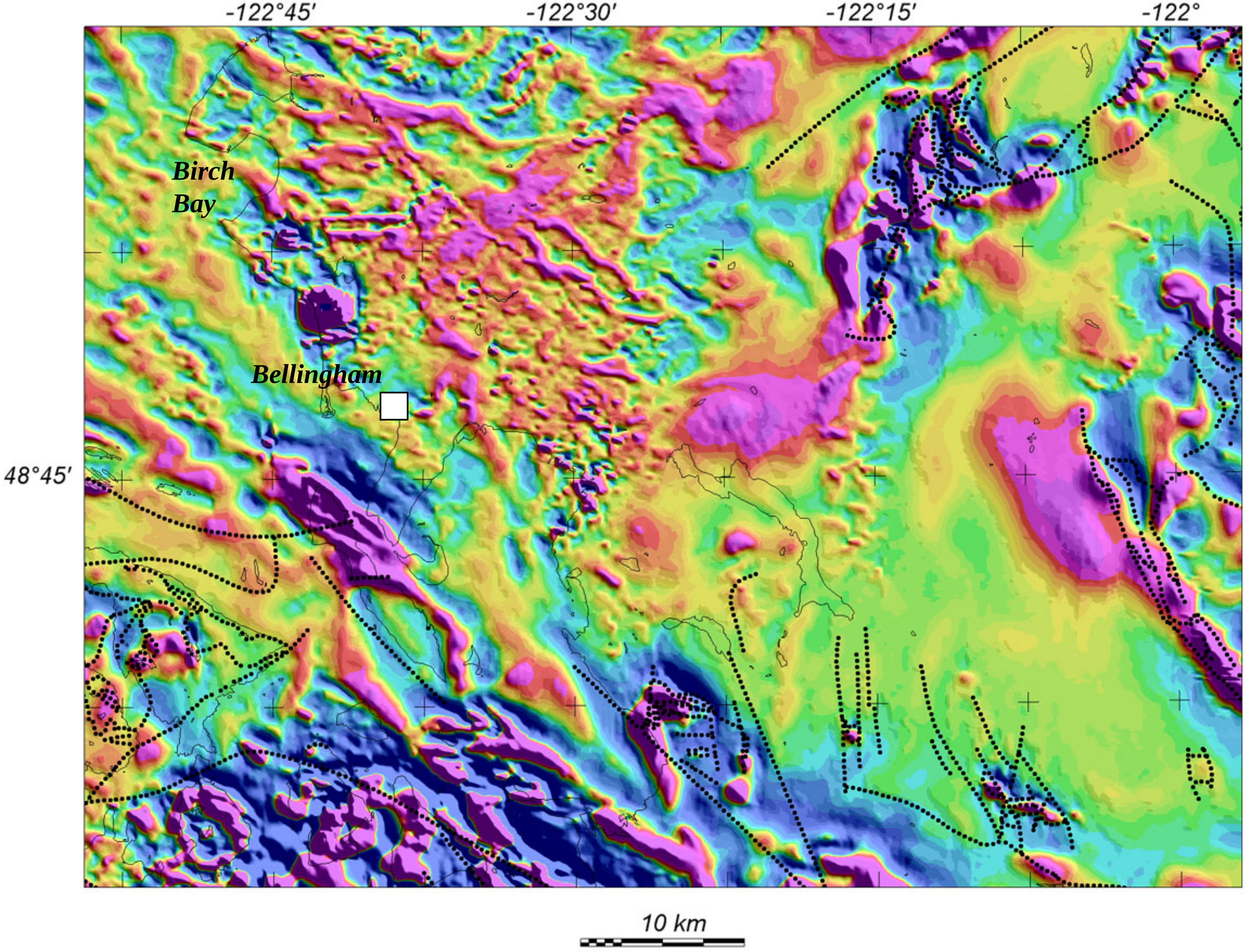
Mustard, P.S., and Rouse, G.E., 1994, Stratigraphy and evolution of the Tertiary Georgia Basin and subjacent Late Cretaceous strata of the Greater Vancouver area, British Columbia, in Monger, J.W.H., ed., Geology and geological hazards of the Vancouver region, southwestern British Columbia, Volume Bulletin 481, Geological Survey of Canada, p. 97-161.

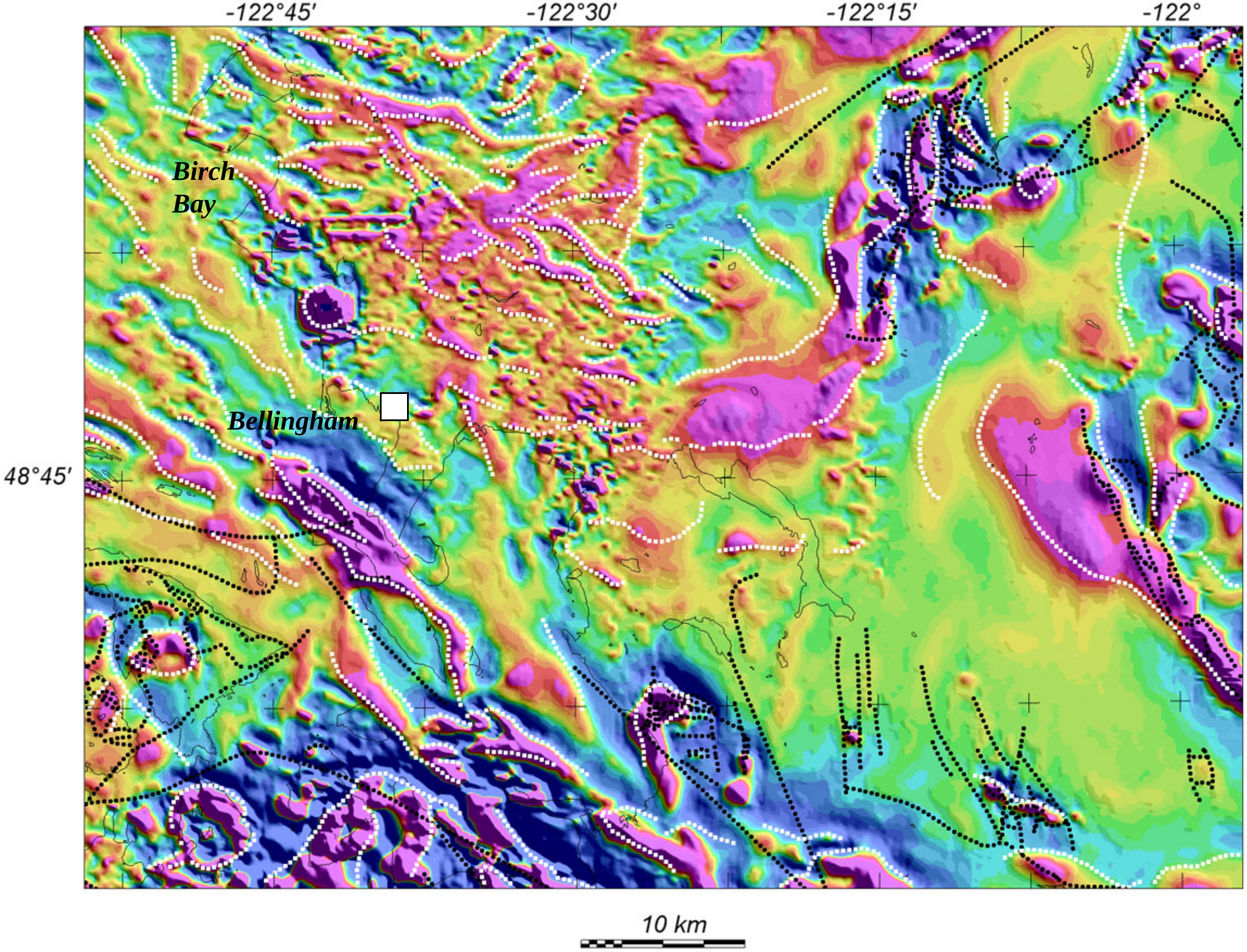

-124°
-123°
-122°
49°
48°
mGal
45
30
15
5
-10
-20
-35
-45
V
BB
Figures 3,4, 5
B
BCF
SJF
LRF
VI
Canada
United States
DMF
EB
SWIF
E
SB
SF
S
TF
T
TB
25 km
Strait of Georgia
Va
British Columbia
Canada
U.S.
K
GI
B
Mt. Baker
Vancouver Island
SJI
Vi
Washington
Strait of Juan de Fuca
33
9
-3
-9
-15
-21
-28
-43
mGal

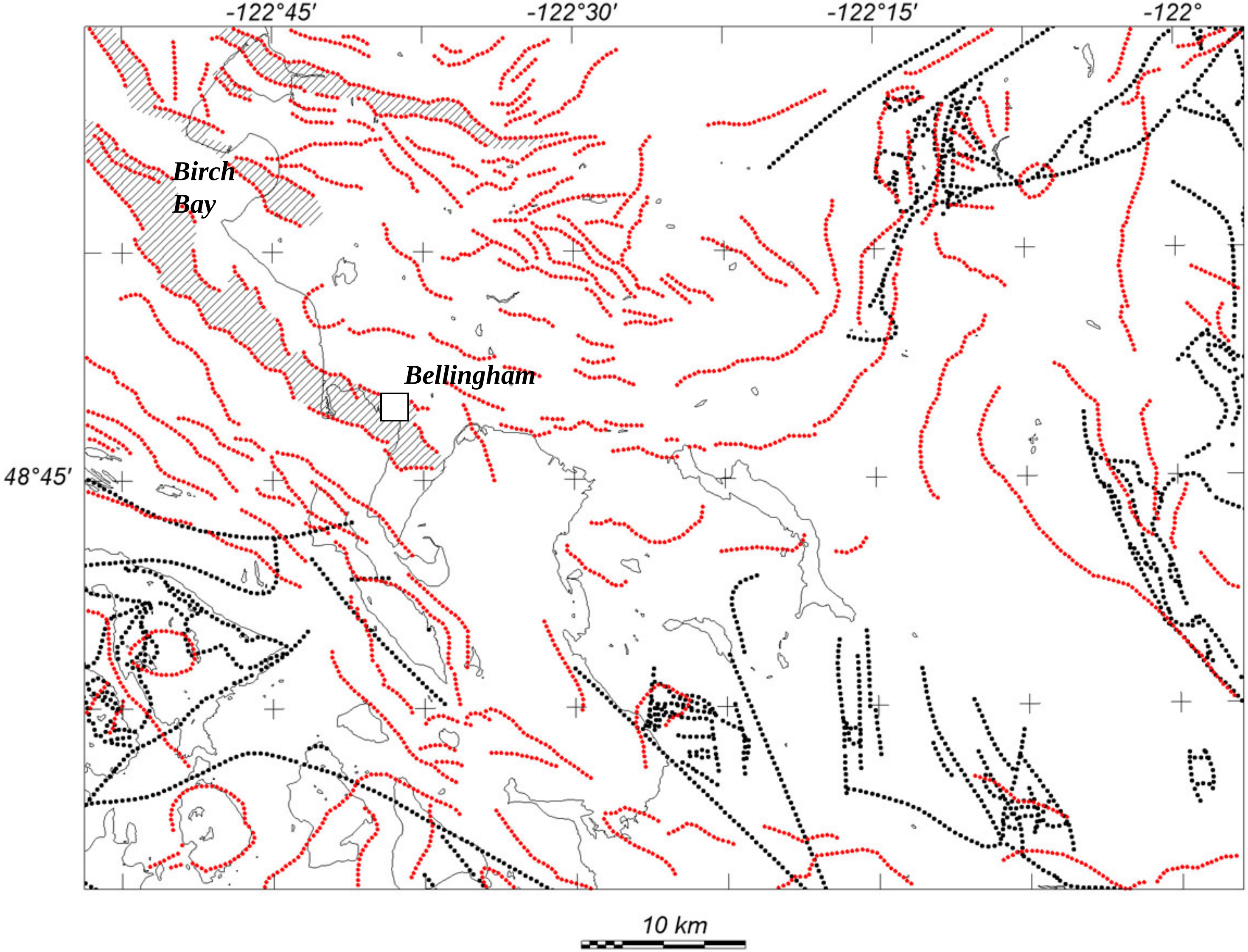


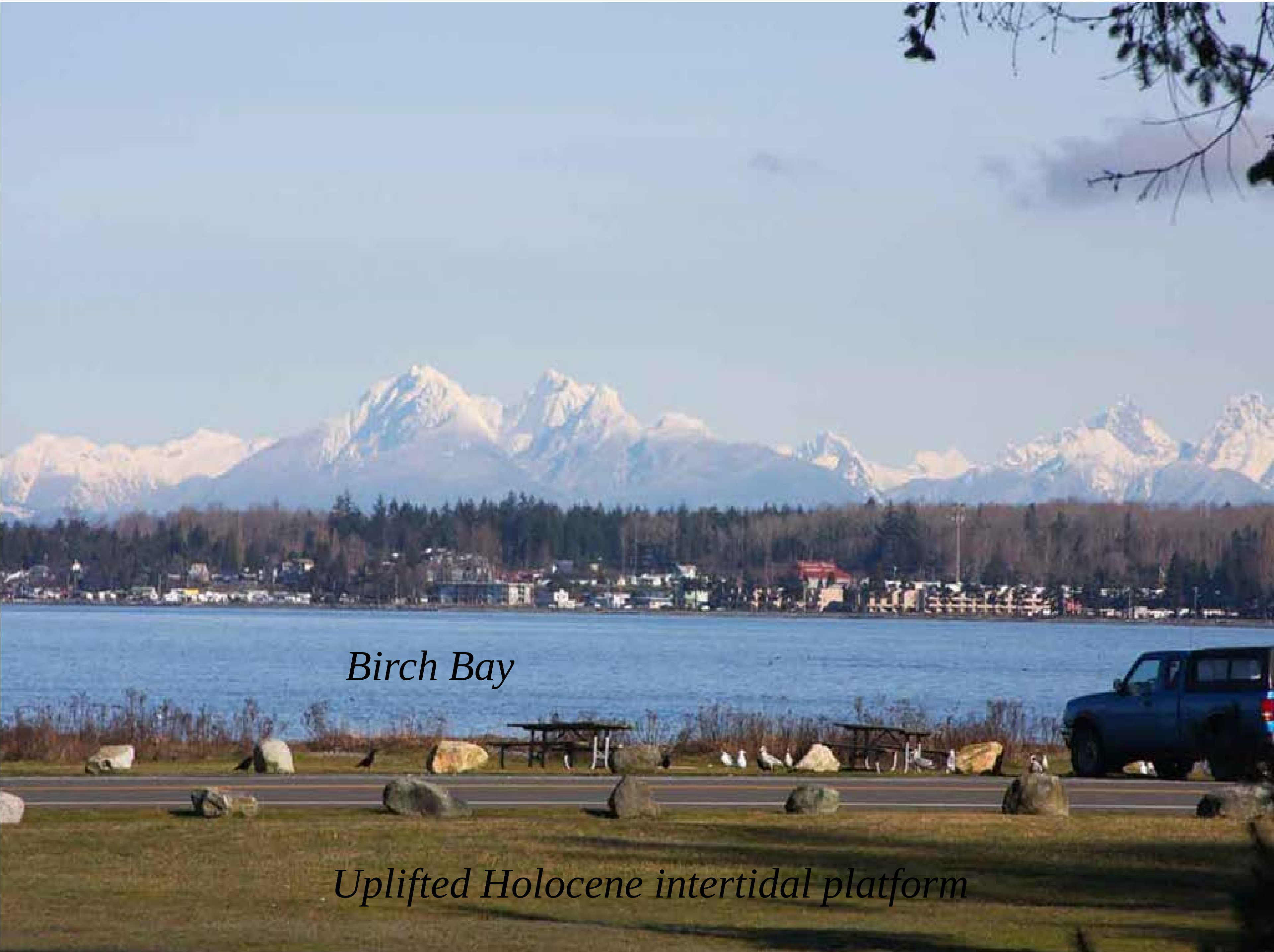
Mustard, P.S., and Rouse, G.E., 1994, Stratigraphy and evolution of the Tertiary Georgia Basin and subjacent Late Cretaceous strata of the Greater Vancouver area, British Columbia, in Monger, J.W.H., ed., Geology and geological hazards of the Vancouver region, southwestern British Columbia, Volume Bulletin 481, Geological Survey of Canada, p. 97-161.

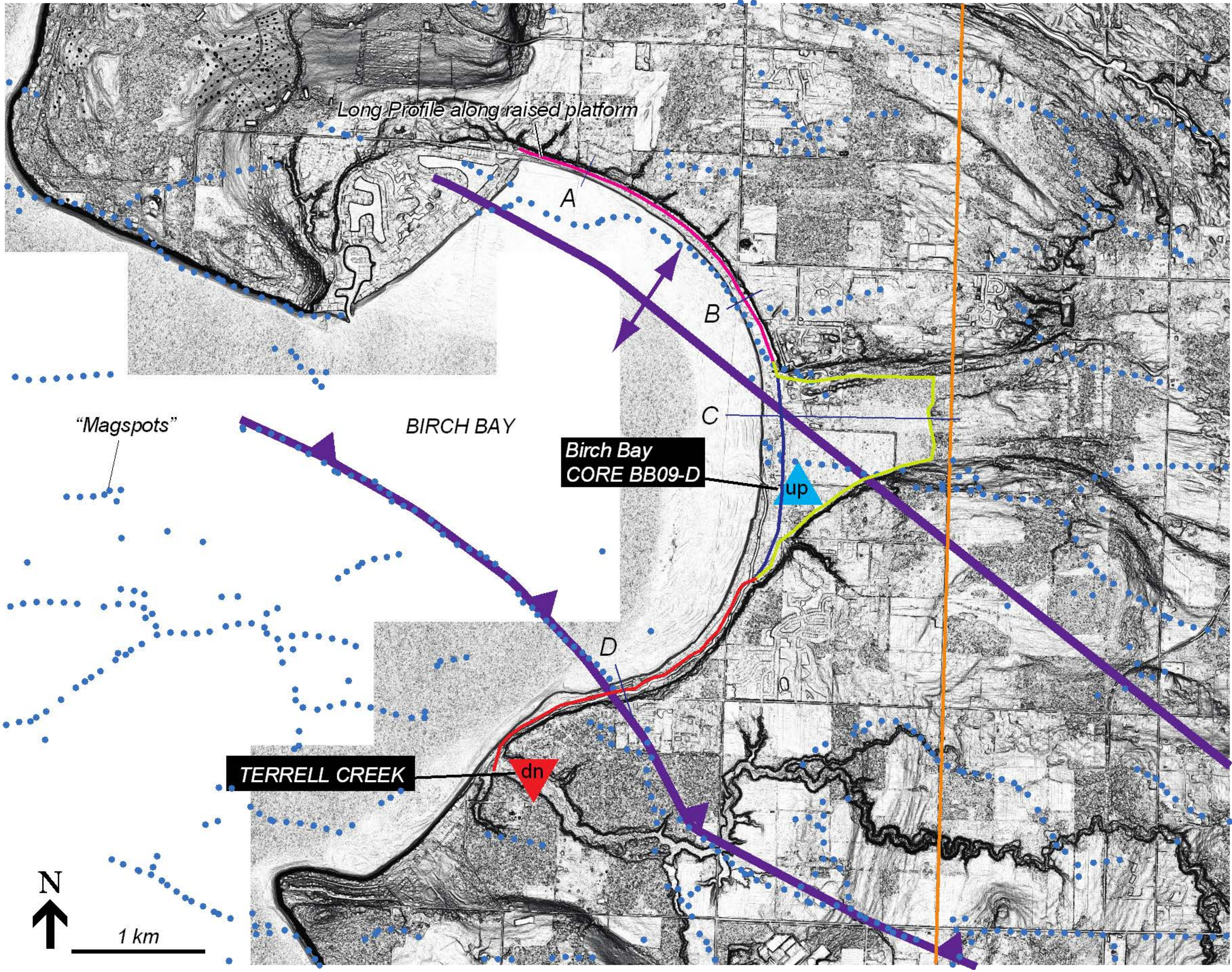

-122°45′
-122°30′
-122°15′
-122°
48°45′
Birch Bay
Bellingham
10 km

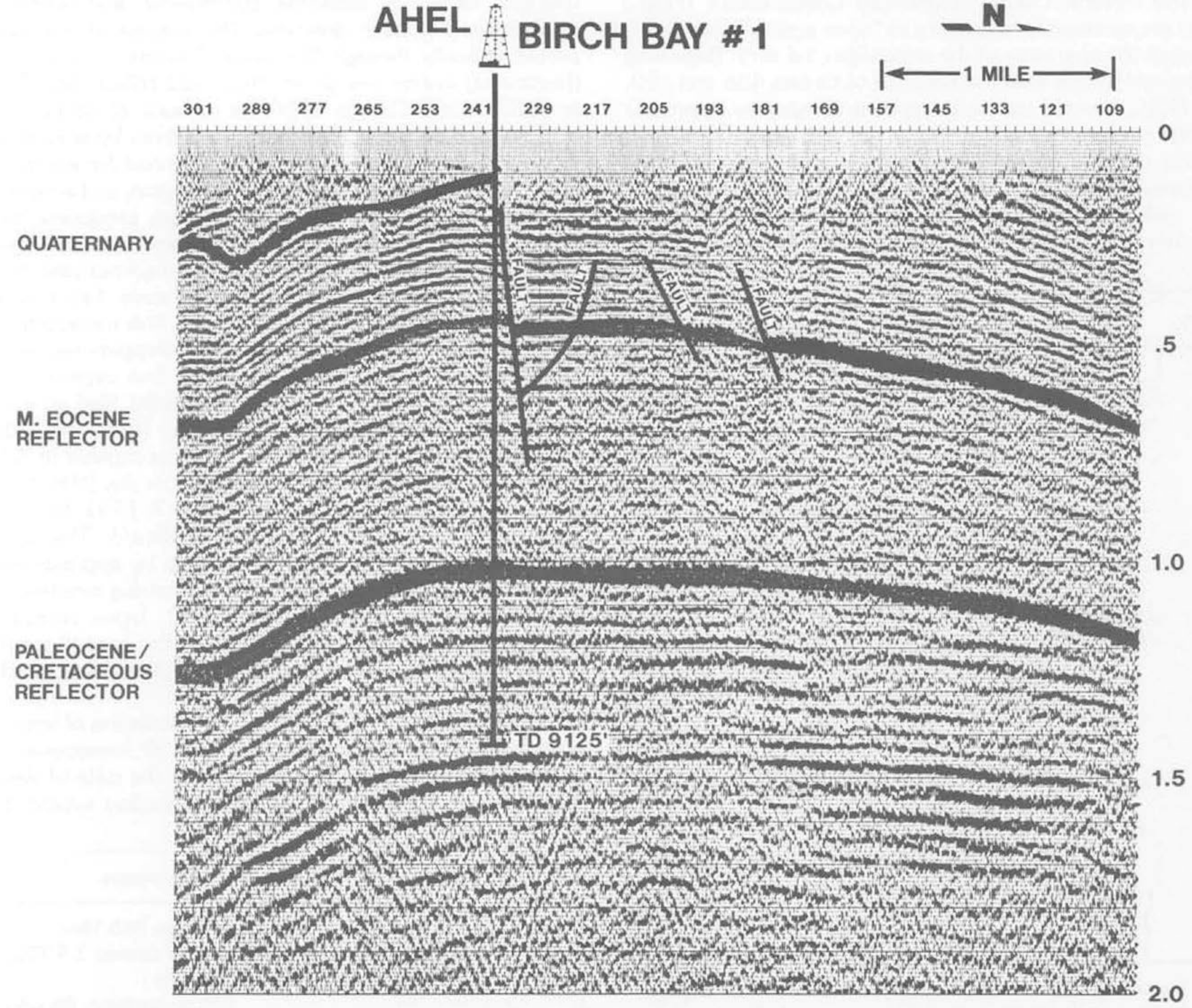

-122°45′
-122°30′
-122°15′
-122°
48°45′
Birch Bay
Bellingham
10 km

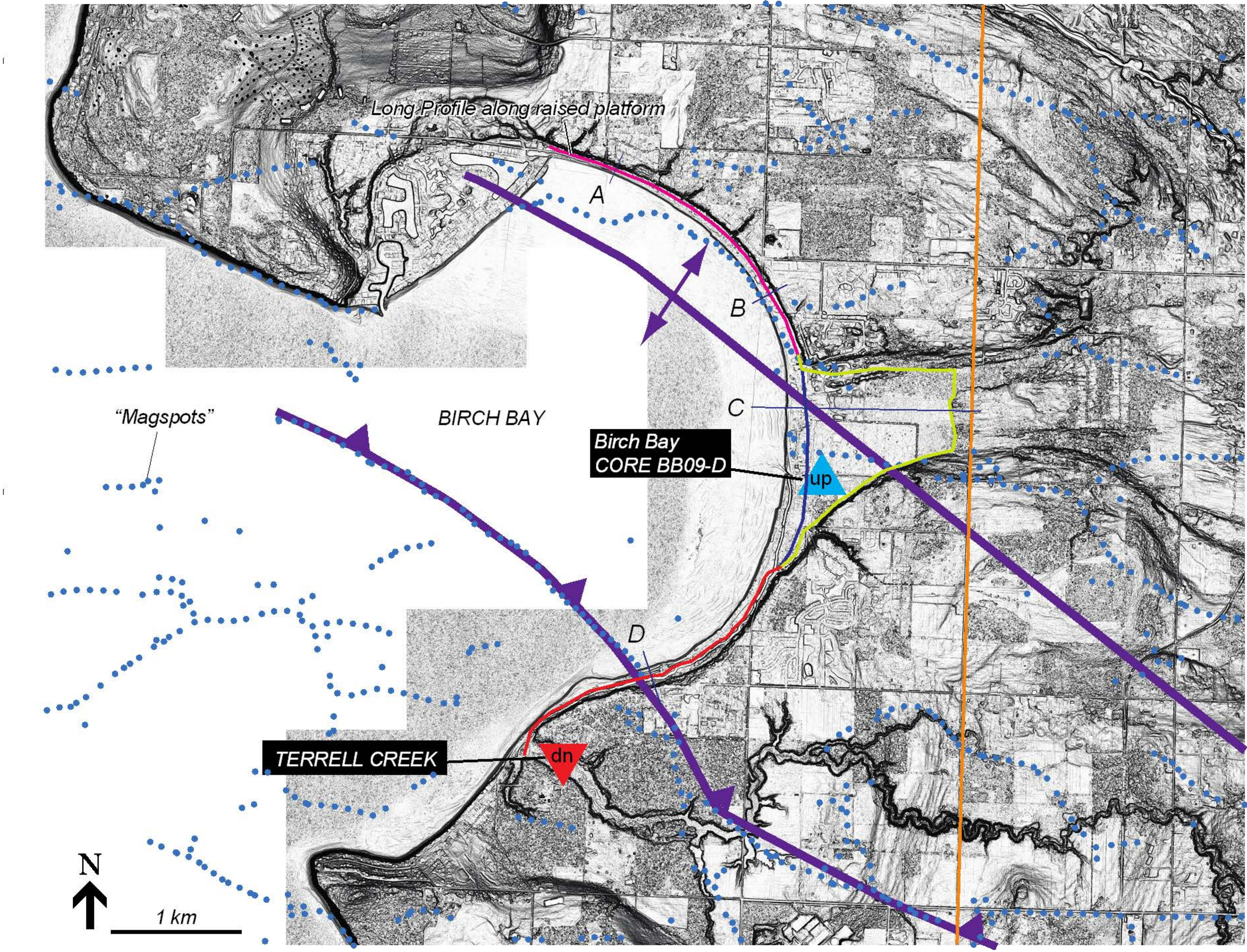

-122°45′
-122°30′
-122°15′
-122°
Birch Bay
Bellingham
48°45′
10 km


-122°45′
-122°30′
-122°15′
-122°
Birch Bay
Bellingham
48°45′
10 km

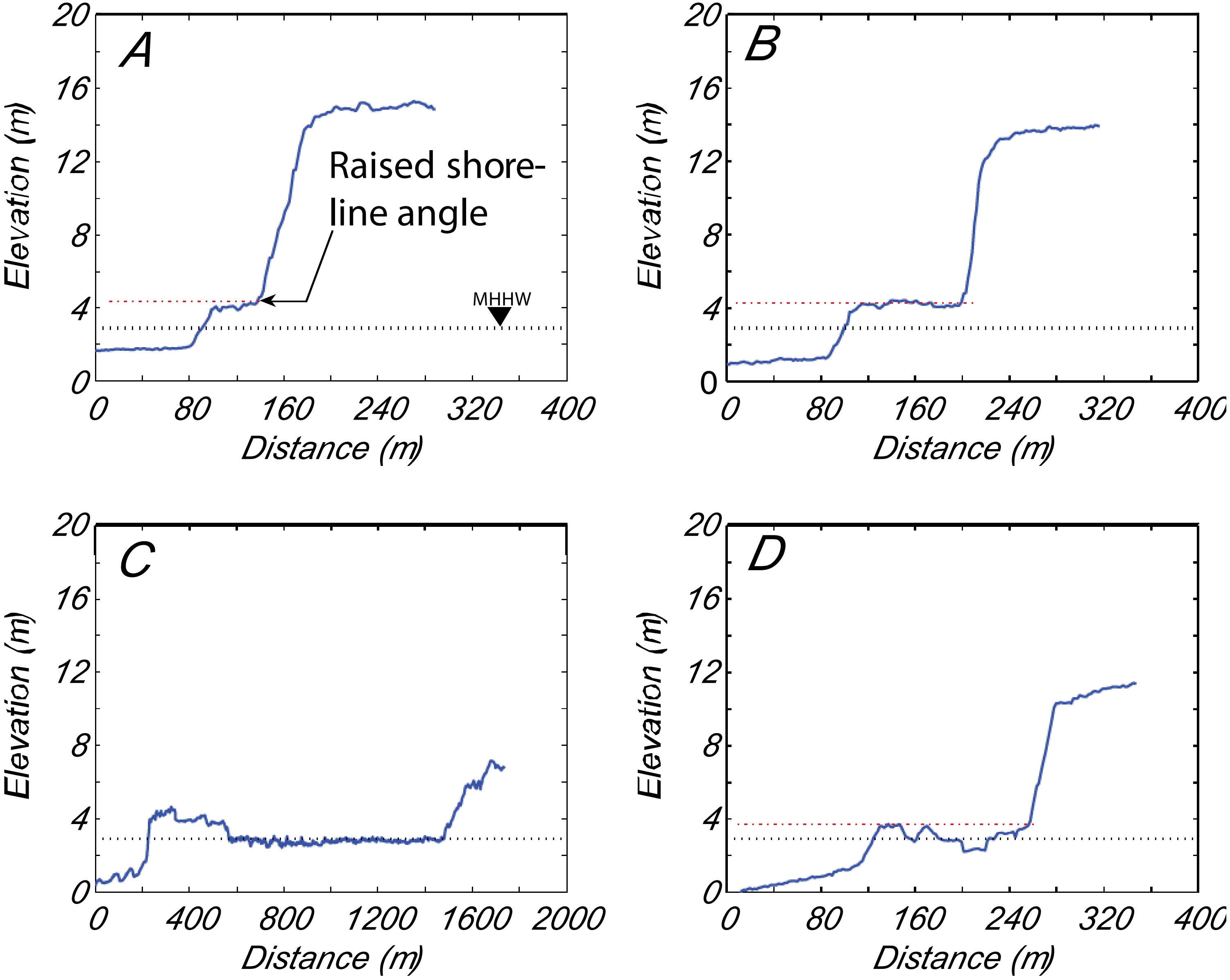

Birch Bay
Uplifted Holocene intertidal platform

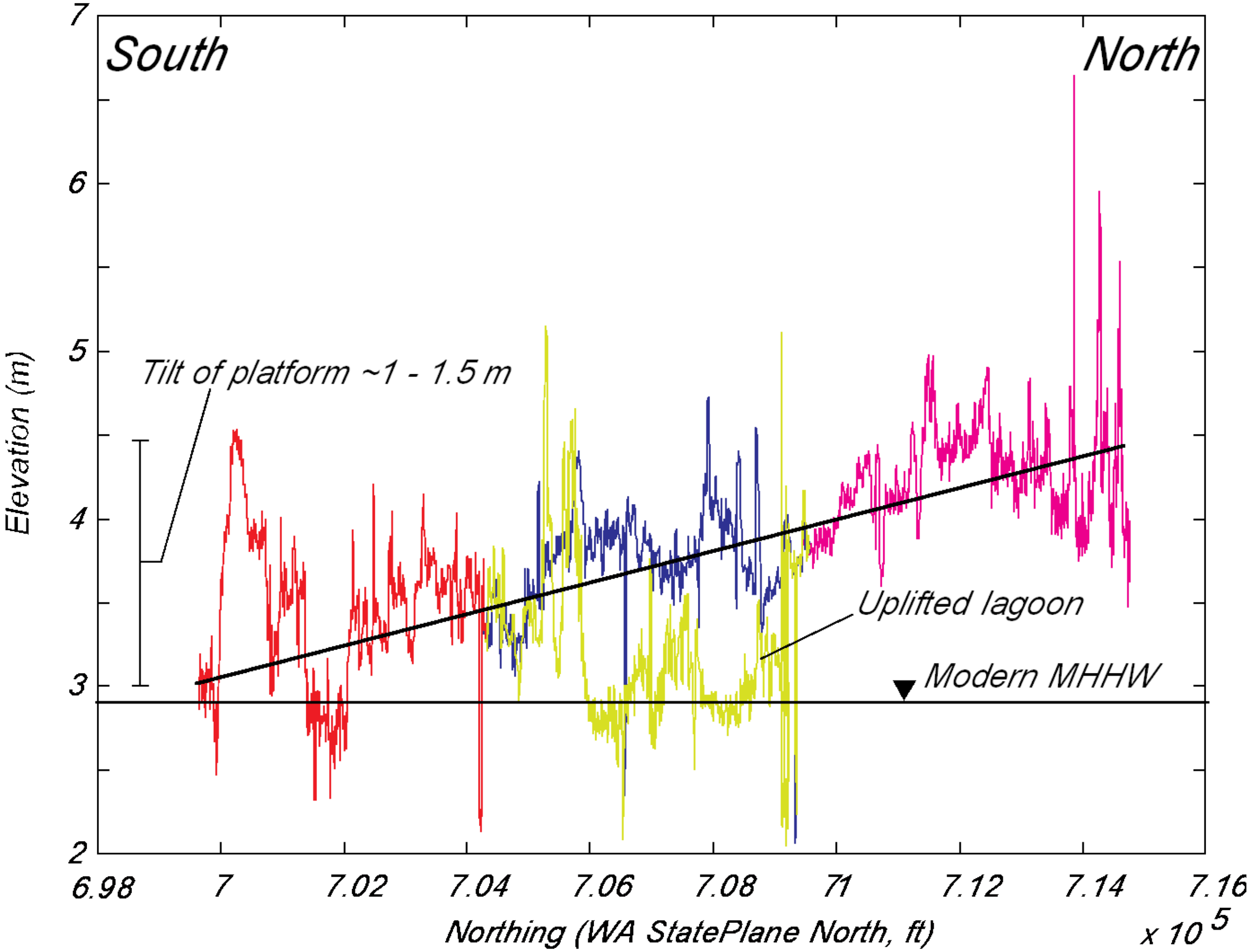

Long Profile along raised platform
A
B
C
D
"Magspots"
BIRCH BAY
Birch Bay
CORE BB09-D
up
TERRELL CREEK
dn
N
1 km


AHEL
BIRCH BAY #1
N
1 MILE
301
289
277
265
253
241
229
217
205
193
181
169
157
145
133
121
109
0
.5
1.0
1.5
2.0
QUATERNARY
FAULT
FAULT
FAULT
FAULT
M. EOCENE REFLECTOR
PALEOCENE/ CRETACEOUS REFLECTOR
TD 9125'



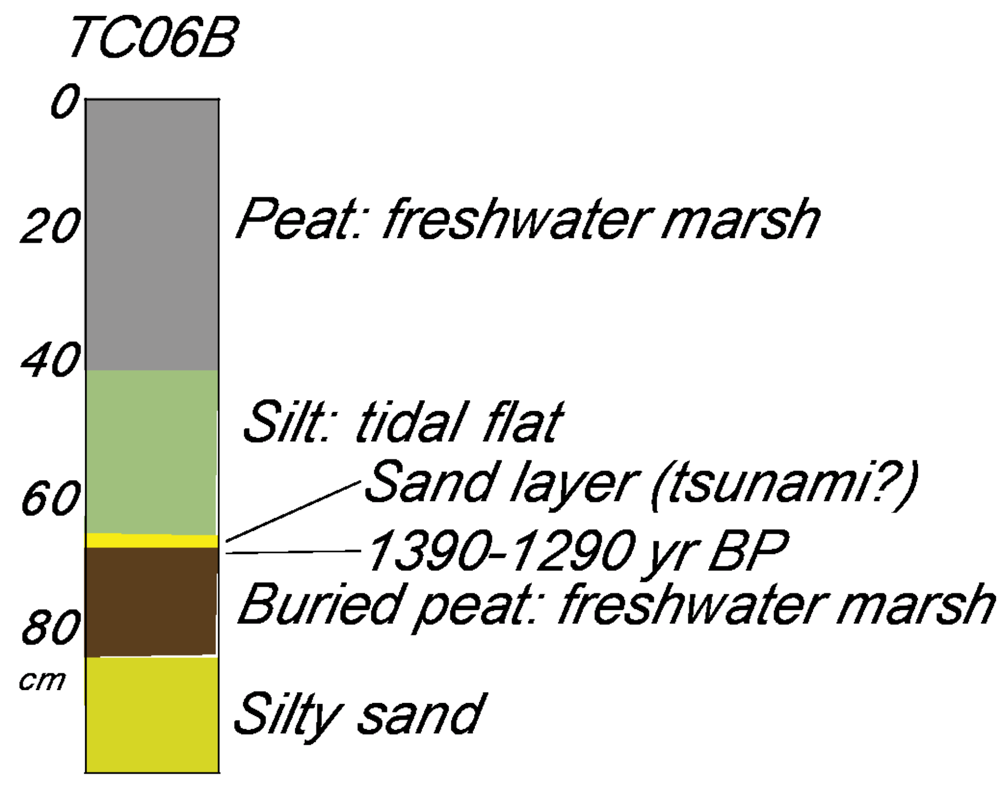
Long Profile along raised platform
A
B
C
D
BIRCH BAY
"Magspots"
Birch Bay
CORE BB09-D
up
TERRELL CREEK
dn
N
1 km


A
B
C
D
Raised shoreline angle
MHHW
Elevation (m)
Distance (m)
0
4
8
12
16
20
0
80
160
240
320
400
0
400
800
1200
1600
2000



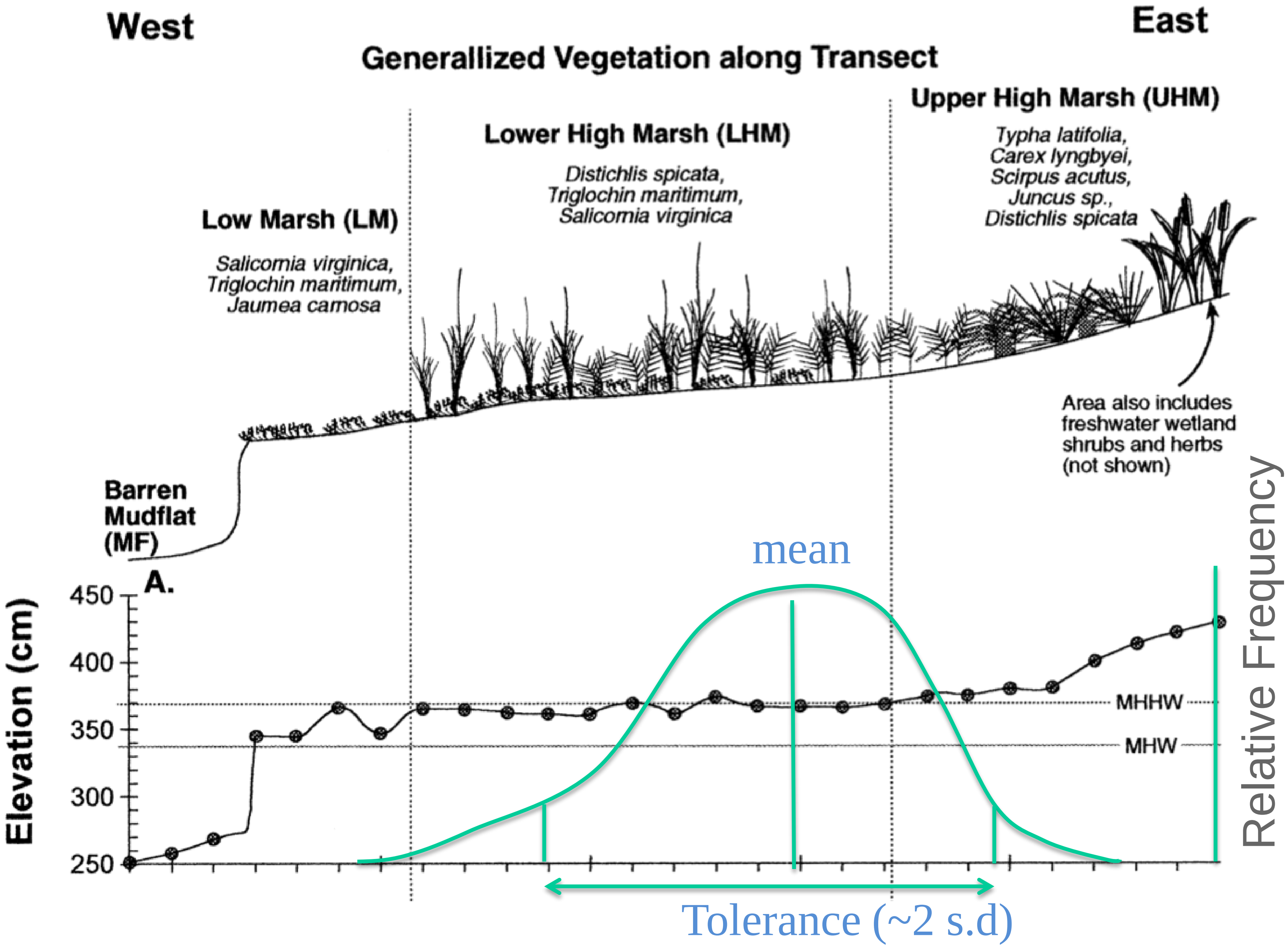
South
North
Tilt of platform ~1 - 1.5 m
Uplifted lagoon
Modern MHHW
Elevation (m)
7
6
5
4
3
2
6.98
7
7.02
7.04
7.06
7.08
71
7.12
7.14
7.16
Northing (WA StatePlane North, ft)
x 10 5

Terrell Creek Marsh Stratigraphy



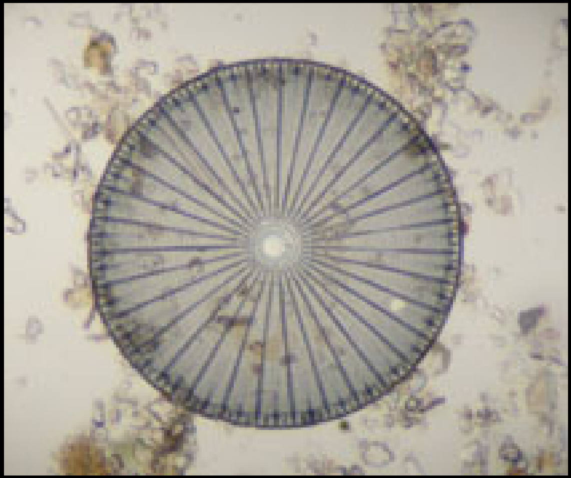
The Terrell Creek marsh is situated landward of a beach berm within the intertidal reaches of Terrell Creek. The marsh is inset within a valley bounded by terraced Pleistocene glacial deposits and the surface layer of the marsh (uppermost 35 cm) consists of freshwater peat. Mud at ~1.4 m depth contains marine mullusk, shells. Within the Terrell Creek marsh, multiple cores uniformly revealed one abrupt major lithologic transition in the upper meter—this transition, at about 0.6 m depth, was from a black peaty soil abruptly upward to a gray to brownish gray mud.

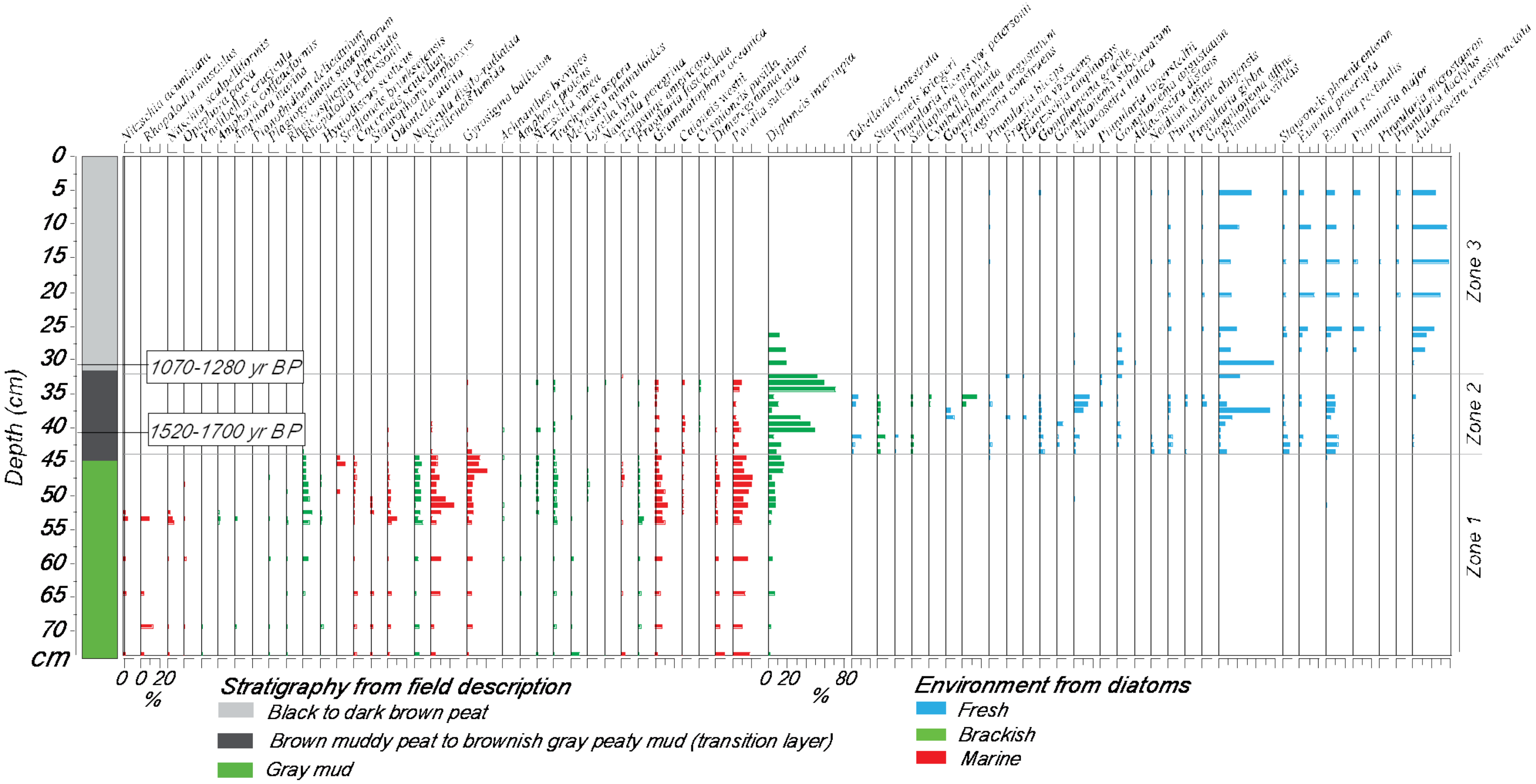
Diatom biostratigraphic data for core TC06B, obtained by sampling across the upper contact of the buried peat, indicates that the site changed abruptly from a peaty freshwater marsh to a tidal mudflat shortly after 1390-1290 yr BP.

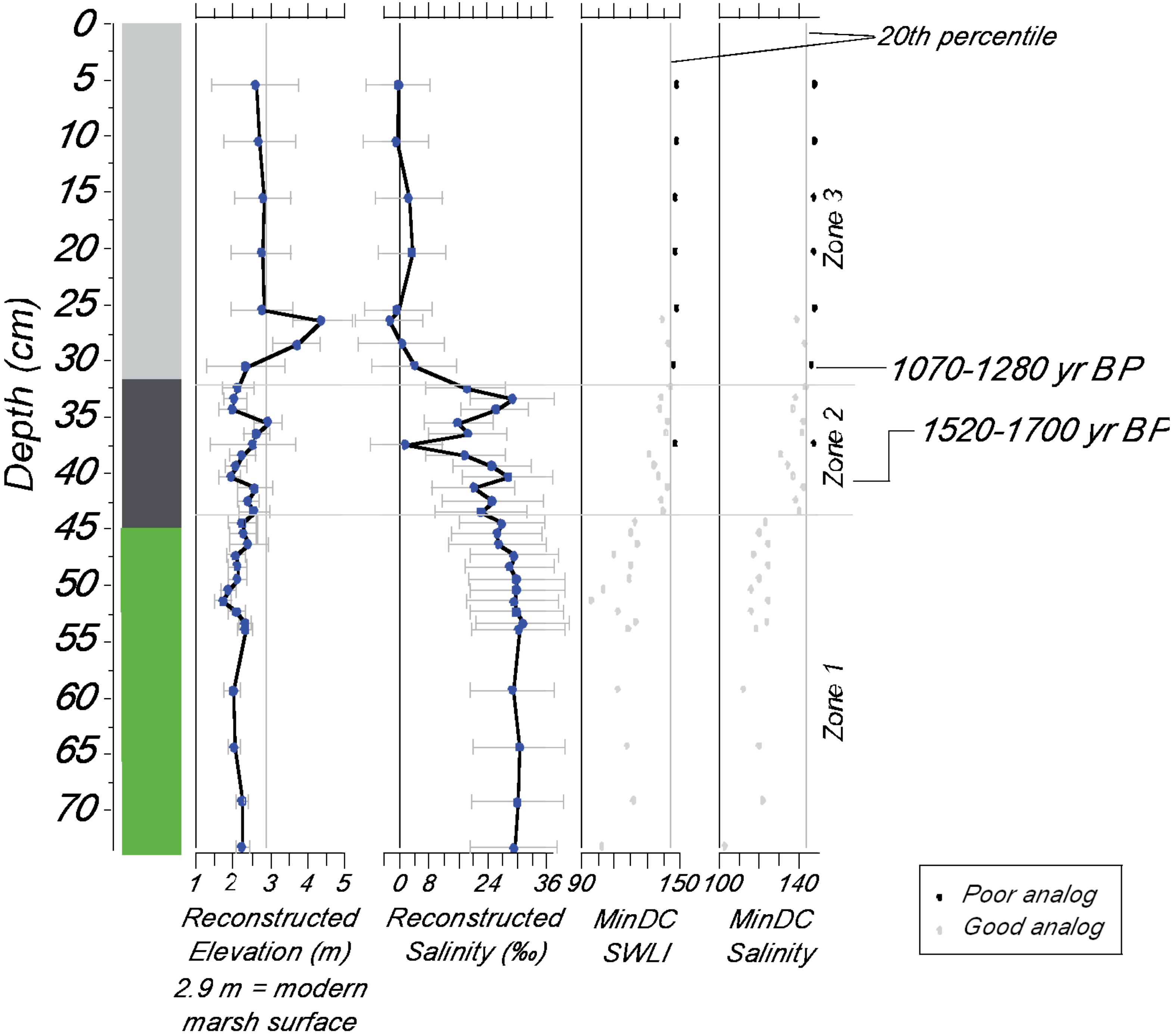

West
East
Generallized Vegetation along Transect
Upper High Marsh (UHM)
Typha latifolia,
Carex lyngbyei,
Scirpus acutus,
Juncus sp.,
Distichlis spicata
Lower High Marsh (LHM)
Distichlis spicata,
Triglochin maritimum,
Salicornia virginica
Low Marsh (LM)
Salicornia virginica,
Triglochin maritimum,
Jaumea carnosa
Area also includes freshwater wetland shrubs and herbs (not shown)
Barren Mudflat (MF)
A.
Elevation (cm)
450
400
350
300
250
MHHW
MHW
mean
Relative Frequency
Tolerance (~2 s.d)

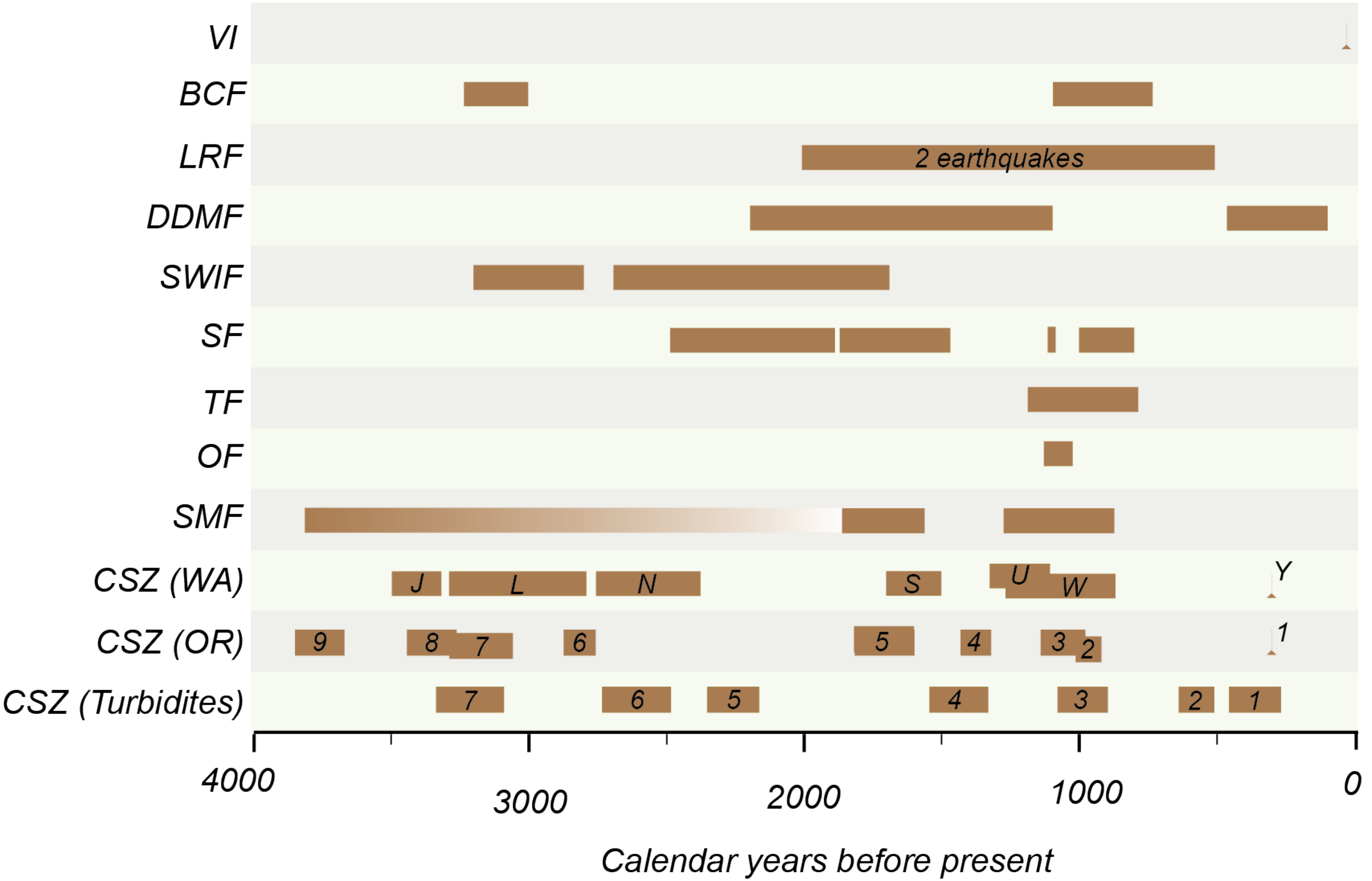
Diatoms – unicellular, golden-brown algae that secrete a siliceous cell wall (valves). Found in freshwater, brackish, and marine environments.

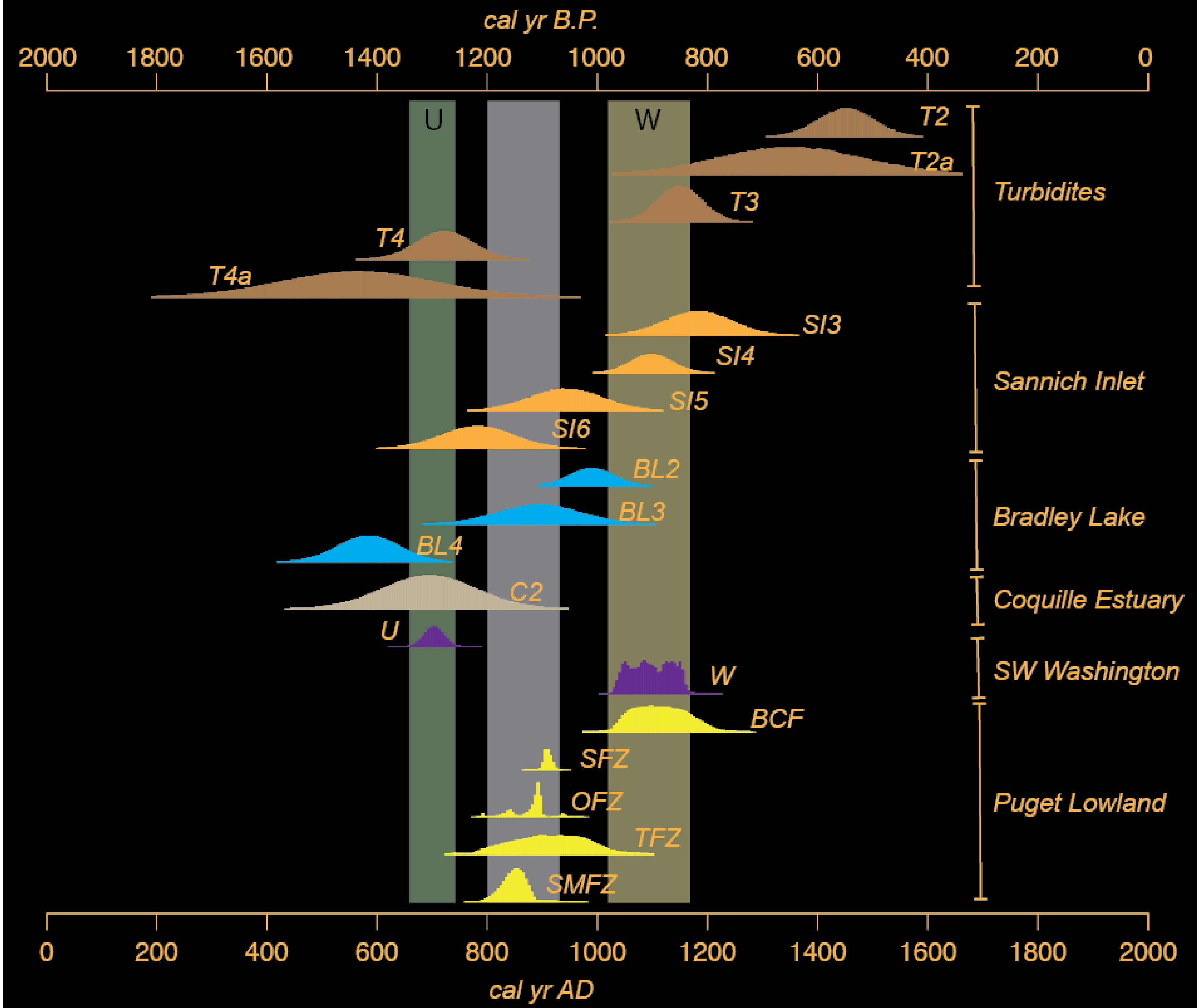
Valves are often identifiable down to species or subspecies levels and many species are specific to certain environments, making them wonderful little organisms to do environmental calibration/transfer function work.




Nitzschia acuminata
Rhopalodia musculus
Nitzschia scalpelliformis
Opephora parva
Parlibellus crucicula
Amphora coffeaeformis
Amphora marina
Planothidium delicatulum
Plagiogramma staurophorum
Rhabdonema abbreviata
Rhopalodia brebissonii
Hyalodiscus scoticus
Scoliotropis brunkseiensis
Cocconeis scutellum
Staurophora amphioxys
Odontella aurita
Navicula digito-radiata
Scolioneis tumida
Gyrosigma balticum
Achnanthes brevipes
Amphora proteus
Nitzschia vitrea
Trachyneis aspera
Melosira nummuloides
Lyrella lyra
Navicula peregrina
Terpsinoe americana
Fragilaria fasciculata
Grammatophora oceanica
Caloneis westii
Cosmioneis pusilla
Dimeregramma minor
Paralia sulcata
Diploneis interrupta
Tabellaria fenestrata
Stauroneis kriegeri
Pinnularia biceps var. petersonii
Sellaphora pupula
Cymbella minuta
Gomphonema angustatum
Fragilaria construens
Pinnularia biceps
Fragilaria virescens
Hantzschia amphioxys
Gomphonema gracile
Gomphonema subclavatum
Aulacoseira italica
Pinnularia lagerstedtii
Gomphonema angustatum
Aulacoseira distans
Neidium affine
Pinnularia abujensis
Pinnularia gibba
Gomphonema affine
Pinnularia viridis
Stauroneis phoenicenteron
Eunotia praerupta
Eunotia pectinalis
Pinnularia major
Pinnularia microstauron
Pinnularia dactylus
Aulacoseira crassipunctata
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
cm
Depth (cm)
1070-1280 yr BP
1520-1700 yr BP
Zone 3
Zone 2
Zone 1
0 0 20
%
0 20
%
80
Stratigraphy from field description
Black to dark brown peat
Brown muddy peat to brownish gray peaty mud (transition layer)
Gray mud
Environment from diatoms
Fresh
Brackish
Marine


Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
1
2
3
4
5
Reconstructed Elevation (m)
2.9 m = modern marsh surface
0
8
24
36
Reconstructed Salinity (‰)
90
150
MinDC SWLI
100
140
MinDC Salinity
20th percentile
1070-1280 yr BP
1520-1700 yr B
Zone 3
Zone 2
Zone 1
Poor analog
Good analog


VI
BCF
LRF
2 earthquakes
DDMF
SWIF
SF
TF
OF
SMF
CSZ (WA)
J
L
N
S
U
W
Y
CSZ (OR)
9
8
7
6
5
4
3
2
1
CSZ (Turbidites)
7
6
5
4
3
2
1
4000
3000
2000
1000
0
Calendar years before present


cal yr B.P.
2000
1800
1600
1400
1200
1000
800
600
400
200
0
U
W
T2
T2a
T3
T4
T4a
Turbidites
SI3
SI4
SI5
SI6
Sannich Inlet
BL2
BL3
BL4
Bradley Lake
C2
Coquille Estuary
U
W
SW Washington
BCF
SFZ
OFZ
TFZ
SMFZ
Puget Lowland
0
200
400
600
800
1000
1200
1400
1600
1800
2000
cal yr AD

For more information:

Earthquake Notification Service (ENS)
- *https://sslearthquake.usgs.gov/ens/*

ANSS – Advanced National Seismic System (USGS)
PNSN – Pacific Northwest Seismic Network
- *www.pnsn.org*